Technical Report 67-53

ADVANCEMENT OF ULTRASONIC TECHNIQUES USING RERADIATED SOUND ENERGIES FOR NONDESTRUCTIVE EVALUATION OF WELDMENTS

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Final Report

30 August 1967

by

B. T. Cross
W. M. Tooley

Prepared under Contract No, NObs-92530
Serial No. SR007-10-04, Task No. 891
for Chief, Bureau of Ships, Code 634B,
Department of the Navy, Washington, D. C.,
by the Research Laboratory, Automation
Industries, Inc., Boulder, Colorado, 80302

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FOREWORD

This final report was prepared by Automation Industries, Inc., under Naval Ship Systems Command Contract NObs 92530. Under this contract a feasibility study was conducted to establish the practicability of using the Delta Technique for nondestructive evaluation of production weldments. The Delta Technique is a unique ultrasonic weld inspection which utilizes reradiated energy for the detection of weld defects. This report includes: an analysis of the physics of reradiated sound energy, the development of a Delta Technique for butt weld inspection, and recommendations for incorporating the Delta Technique into production weld inspection.

Personnel involved in the execution of this program includes: (a) Automation Industries, Inc., Mr. G. J. Posakony, Mr. W. M. Tooley, and Mr. B. T. Cross, (b) Navy Project Engineer, Mr. John Gleim, Code 634B, and (c) Consultants, Dr. S. Maley (University of Colorado) and Mr. R. Nickerson, (Lawrence Radiation Laboratories, Berkeley, California).

The program was scheduled to start on 23 June 1965, and to be completed on 25 June 1966. Due to unforeseen vendor delays, a no cost time extension was requested in March 1966. On 15 April 1966, the request was granted in the form of Contract No. NObs 92539, Mod. 2, stating, "Pursuant to the provisions of the section of the schedule entitled 'Period of Contract', the Contracting Officer hereby elects to require you to continue performance of work hereunder until the estimated cost shall have been expended".

SUMMARY

No single testing method presently exists that will provide a complete nondestructive evaluation of structural welds. In the United States radiographic techniques are widely accepted. Many specialized radiographic techniques have been developed for investigating particular weldments; however, these techniques have specific limits and certain types of defects cannot be detected. Ultrasonic inspection techniques have supplemented radiography, but as currently used, ultrasonics are not a universal tool. Present ultrasonic techniques have specific limitations and the results are often difficult to interpret. Most ultrasonic techniques do not provide permanent inspection records.

~~The Research Laboratory of Automation Industries, Inc.~~, has developed an ultrasonic inspection technique called the Delta Technique. This technique has many advantages over present weld inspection techniques. The Delta Technique is not sensitive to any preferential defect orientation and it can provide a permanent record of the test results.

Delta inspections have been conducted successfully for both thick and thin butt welds and various configurations of tee welds. An inspection speed of 50 feet per hour was obtained in the laboratory. This was the maximum operating speed of the laboratory mechanical fixturing system and not the maximum operating speed of the Delta Technique.

As a result of this program, we have defined the operating parameters necessary for inspecting butt welds with the Delta Technique. ~~These parameters are listed in Table I in the appendix.~~ It is possible to assign operating parameters for a butt weld of given thickness in a specific material. Manual and automatic Delta weld inspection techniques have been studied. Each are applicable to inspection of the hull welds used in submarine fabrication. The Delta Technique can provide the Navy with a means for rapid, economical evaluation of butt welds and, potentially, other weld configurations, such as the tee weld.

I. TECHNICAL DISCUSSION OF WORK PERFORMED

1.0 Background

With the high performance vessels of the modern Navy, nondestructive evaluation of structural welds has become extremely important. It is general practice to inspect weldments with two and, sometimes, three different NDT methods because of the inherent limitations of present weld evaluation techniques. The cost of weld evaluation is increasing. The cost of radiographic inspection alone is high due to the material consumption; however, because of radiation hazard no other work can be performed on the structure during inspection. An inspection method such as ultrasonics which could evaluate a weld internally without the accompanying radiation hazard would result in a large cost reduction. Even more important would be the savings resulting from an inspection method which could replace all other inspection methods, particularly, a new method that could rapidly scan a weldment and accept the good weld. Unacceptable weld could be critically evaluated with several NDT methods, (36) after the good weld had been accepted by the rapid inspection technique.

The Delta Technique is an ultrasonic nondestructive testing method for rapid weld acceptance. This technique is relatively insensitive to defect orientation; therefore, rapid weld inspection with high reliability is possible. Welds can be inspected with the Delta Technique either manually or automatically and automatic Delta weld inspection provides a permanent record of the test.

2.0 Theory of Delta Operation

To understand the operation of the Delta Technique, it was necessary to identify and define the physics of the Delta phenomena and the parameters which govern its operation. The theory of the Delta phenomena was developed from classical energy equations (18, 33, 34, 41) and from empirical data collected during various studies (13, 14, 15) of the Delta Technique. For some time, certain phenomena of the Delta operation has been used successfully in specific applications, even though the phenomena had not been analyzed or defined. In analyzing the Delta theory, we assigned specific meanings to certain terms. The following terms are used throughout the text and are defined as:

A. Transmitted Beam - The transmitted beam is the longitudinal wave originating at the transmitter search unit and incident upon the part surface at a specified angle (α).

B. Transmitted Shear Beam - The transmitted shear beam is the refracted shear wave propagating in the part as a result of the transmitted beam striking the part surface. The angle of incidence between the transmitted beam and the part surface is beyond the critical angle for transmission of longitudinal energy into the part.

C. Interface - The surface forming the boundary between two adjacent media of different acoustical impedance.

D. Redirected Energy - Any energy propagating in the part in a direction different than that of the transmitted shear beam. Redirection is caused by an interaction between the transmitted shear beam and an interface. Redirected energy can be reflected, mode converted, or reradiated energy.

E. Mode Conversion - Ultrasonic energy will propagate in an elastic media in three principle modes: longitudinal, shear, and surface. Mode conversion is the change of ultrasonic energy from one mode of propagation to another as a result of striking an interface.

F. Reradiated Energy - An omnidirectional, coherent ultrasonic wave generated at an interface as a result of interface excitation caused by an impinging ultrasonic beam. This definition is based on a hypothesis formed by this research group.

The Delta theory was developed by explaining the observed Delta phenomena with established equations and facts. Three distinct ultrasonic waves were observed to occur as a result of an interaction between the transmitted shear beam and an interface. These waves are identified in the Schlieren image shown in the photograph of Figure No. 1. A sketch in the lower half of Figure No. 1 gives a ray analysis of the untrasonic energy behavior within the part. Each of these waves were analyzed by using a test sequence and model oriented for that particular occurrence.

The first model contained a vertical interface that opened to neither the top or the bottom surface of the part, see Figure No. 2A. Reflection and mode conversion of the transmitted shear wave were predicted by Snell's Law. In Figure No. 3, Snell's Law is stated and the predicted wave behavior is illustrated in a sketch. The interface was assumed to be a metal-to-air interface which is representative of the condition resulting from a crack or lack of penetration in a weldment. The transmitted shear beam (E_s) strikes the interface at incident angle β causing a reflected shear wave (E_{sr}) and a mode converted longitudinal wave (E_{mc}). Mode conversion at the interface only occurs when the incident angle (β) lies within an angular region defined as:

$$0° < \beta < \sin^{-1} V_s/V_l, \qquad (1)$$

where V_s is the shear wave velocity in the part and V_l is the longitudinal wave velocity in the part. For steel, the angular region for β lies between 1° and 33°. Since the relationship between angle β and angle α is determined by Snell's Law, the specified angular region for β can be related directly to a corresponding angular region for α which lies between 22.6° and 27.4° (for steel). Snell's Law predicted the existence of each wave within the specified angular regions, but it did not define the energy partition at the interface for the resulting waves. Energy distribution equations (17, 33, 39) were used to plot curves relating the energy partition at the interface versus the angle of incidence (α) of the transmitted beam. Calculated curves illustrating the energy partition at the vertical interface are shown in Figure No. 4. Because of the large acoustical impedance mismatch between metal and air, the quantity of energy transmitted through the interface is negligible.

A second mode conversion occurs at the bottom surface of the part, see Figure No. 5. The mode converted longitudinal wave upon striking the bottom surface is split into a reflected longitudinal wave and a mode converted shear wave. The partition of energy at this point is shown in the curves of Figure No. 4.

The reradiated energy was analyzed empirically. Classical wave equations do not predict the existence of this energy mode; therefore, an analysis of this energy must be hypothetical. Ultrasonic energy was observed in the plane of the interface at both surfaces. A velocity value for this energy propagation was determined by measuring the total travel time and the total distance traveled, see Figure No. 6. The total travel path was divided into segments that were identifiable with respect to mode of energy propagation and wave velocity. Time of travel for the sound waves propagating from points 0-1, 1-2, and 3-4 were calculated and verified experimentally. The modes of energy propagation between these indicated points are known. Wave propagation from point 2 to 3 was the only segment for which no predictions could be made from classical wave equations. An empirical velocity value was established for the wave (2-3) by dividing the physical length (2-3) by the travel time from 2 to 3. This measurement was made many times. Calculated velocity values were averaged to give a statistical value for the velocity of the wave. The statistical velocity value was 5.76 millimeters per microsecond. We assigned the term "reradiated energy" to the ultrasonic energy propagating between points 2 and 3. Longitudinal wave velocity for the material was 5.82 millimeters per microsecond. Since classical wave equations establish discrete velocity values for which stress waves may travel in an isotropic media, it was assumed that the reradiated energy propagates in a longitudinal or compressional mode at longitudinal wave velocity. According to wave equations (2) and (3), [18, 34, 41]:

longitudinal (compressional) wave velocity $V_l = \sqrt{\frac{K + 3/4\mu}{\rho}}$ (2)

Shear (transverse) wave $V_t = \sqrt{\frac{\mu}{\rho}}$ (3)

K = bulk modulus of elasticity,
ρ = density,
μ = shear modulus of elasticity,

both the shear and longitudinal waves travel at velocities determined by physical constants of that material. Therefore, it is logical to assume that reradiated energy is longitudinal energy.

The second model was a rectangular solid made from steel with a hole drilled into the side to provide a cylindrical metal-to-air interface, see Figure No. 2B. The same analysis was made for this model by considering the cylindrical interface to be composed of many very narrow planar segments. Ultrasonic waves behaved much the same at these planar segments as they did at the large vertical interface. However, each segment was analyz^d separately because the angle of incidence (β) was different for each segment. It was not possible to clearly identify the presence of reradiated energy in this test because the reradiated energy and the mode converted longitudinal energy propagated at the same velocity from the interface.

A strong indication of the presence of reradiated energy was obtained from a modification of the second test model, see Figure No. 2C. A rectangular bar was fabricated into a test sample having a cylindrical surface at one end. The cylindrical surface revolved about the test hole drilled in the bar at point A. Mode converted energy is dependent upon the angle of incidence of the transmitted shear beam; therefore, mode converted energy would not be normal to the cylindrical surface completely around the circumference from 0° to 180°. An ultrasonic wave was detected normal to the cylindrical surface from 0° to 180°. This wave was detected with a flat search unit. A flat lens and crystal will respond with maximum sensitivity to an ultrasonic wave striking the surface at an angle within ±3° of normal. Results of this experiment established the following facts:

A. The high amplitude energy detected at the cylindrical surface was restricted to a range within ±3° of normal.

B. The measured velocity of the energy propagation from the test hole to the cylindrical surface was longitudinal wave velocity.

C. The energy was continuous at the surface from 0° to 180°.

Fact A indicated that the energy propagated radially from the test hole. Fact B indicated a longitudinal wave. Fact C established the existence of this wave completely around the circumference and implied that it originated at the center of revolution (test hole) of the surface. These facts concur with the definition we assigned to reradiated energy.

Another test model was made containing interfaces of various shapes and orientations. See Figure No. 7. Delta tests were conducted on this sample primarily to confirm the assumptions that were made in earlier experiments. The following results were obtained:

A. Energy traveling at longitudinal velocity was detected at the top surface of the part directly above each interface boundry.

B. Energy received from the spherical interface caused the largest indication.

C. The energy received from the spherical interface caused the highest amplitude signal measured for any interface.

These results are interpreted in the following paragraph:

A. The time interval used for signal acceptance excluded all signals that did not propagate directly from the interface to the top surface at longitudinal wave velocity. Since the transmitted shear beam propagated into the part from the top surface, the mode converted longitudinal energy would not be directed toward the top surface by an interface other than the spherical interface. Therefore, it was assumed that the energy detected above the interfaces, except the spherical interface was reradiated energy.

B. The recorded indication of the spherical interface was larger than the recorded indication of the planar interfaces. Analysis of the spherical interface using a planar segment concept predicted a spherical redirection pattern from this interface. This spherical redirection pattern caused the energy at the top surface to spread over an area larger than the pattern of redirected energy from a planar interface. A spray of energy would cause a larger indication to be recorded.

C. The highest amplitude signal was received directly above the spherical interface. Since the curvature of the interface redirects both reradiated and mode converted energy toward the top surface at the same velocity, two modes of redirected energy are received simultaneously. The net effect of two waves arriving within the same time interval accounts for the increased amplitude of the redirected energy signal.

To support the assumption that reradiated energy originates at the interface boundries, a test piece was designed to allow redirected energy to be measured in the interface plane completely around the periphery of the test piece This test is shown in Figure 8 B. Ultrasonic energy propagating into the part from one end was normal to the interface (the flat end of the test hole). Therefore, the incident energy was reflected back along the original path. A receiver search unit was placed on the cylinder wall in the plane of the test hole end. The receiver search unit had a flat lens which was very sensitive to energy striking the lens at an angle less than ±3° from normal, thereby insuring that the high amplitude energy measured was within ±3° of perpendicular to the cylinder wall. Measured velocity of the redirected energy was longitudinal wave velocity. Also the peak signal amplitude was measured in the interface plane and the signal amplitude remained constant completely around the periphery of the piece. Although, in this test, the incident energy was longitudinal, it seemed improbable that longitudinal energy reflected from the hole edges would cause a received signal of equal amplitude around the periphery of the piece. The frequency of the test was varied to study the effect on the received signal amplitude. Tests conducted at 1.0, 2.25, and 5.0 MHz revealed no change in received signal response with respect to frequency; however, small amplitude change was present due to the various search unit combinations. Amplitude changes generally accompany search unit changes. A large amplitude decrease with frequency reduction is normal. Since the amplitude did not decrease, the method of energy redirection from the test hole was considered to be reradiation rather than reflection.

2.1 Test Parameters

The various parameters which govern the Delta operation must be defined if the Delta Technique is to be used for inspection of production weldments. A data sheet established for each weld configuration and material would allow any weld to be inspected by simply selecting the proper parameters. Parameters which govern Delta operation are listed and defined below:

A. The Incident Angle of the Transmitted Beam (α).

   This angle determines the quantity of energy that will be transmitted into the material. It also determines the angle of redirection that mode converted energy will follow. A compromise between the two insures optimum Delta operation. The optimum angle (α) for steel is 23.5°. At this angle, the transmitted shear beam propagates at an angle of 60° from normal in steel.

B. The Separation Distance and the Water Path of the Search Units in the Delta Configuration.

These distances determine the thickness of material which can be inspected with a given set of search units. The separation distance between the two search units, and the water path must meet the following requirements:

(1) The intersection of the transmitted shear beam and the receiver search unit axis must occur in the center or mid-thickness of the plate.

(2) The transmitter search unit must have a water path that positions the most usable portion of the transmitted shear beam in the weld region directly under the receiver search unit.

(3) The receiver water path must be set for the most effective region of capture for the particular search unit used. Effective region of capture is that conical region in which any ultrasonic wave striking the search unit will cause a resulting electrical response from the piezoelectric crystal element. For example, a 0. 750 inch diameter element with a 1. 125 inch radius lens has an adequate region of capture for inspecting 0. 500 inch to 0. 750 inch weld thicknesses.

C. The Transmitter Search Unit

The transmitter search unit must have an effective beam diameter great enough to cover the material thickness when measured in the vertical width of the receiver region. (See sketch in Figure No. 9). Various methods may be used to increase the effective diameter of a given transmitter search unit size. A fixed divergent lens will increase the beam spread of the transmitted shear within the material. The transmitter search unit can be moved perpendicular to the weld seam in an in-and-out motion which increases the effective beam diameter by scanning. Curved or shaped crystal elements can be used in construction of the search unit to increase the beam diameter.

D. The Receiver Search Unit

The receiver search unit must have an effective region of capture sufficient to collect the desired flaw information. The region of capture is determined by the amount of flaw information which must be collected from a given weldment. Refer to Figure No. 9. For example, if all modes of redirected energy are to be received, the region of capture must be great enough to collect reradiated energy directly above the flaw, mode converted energy slightly

behind the flaw, and reflected mode converted shear energy still further behind the flaw. Reference to "behind" the flaw indicates the region between the receiver search unit axis and the transmitter search unit.

E. Test Frequency

Test frequency determines the size of defect which can be detected. Other factors, such as defect shape, and acoustic impedance mismatch between parent material and defect, influence the detection of defects; however, frequency is a controllable factor which the inspector may vary to enhance the detection capabilities of the system. Since a flaw or interface is essentially an energy radiator, more usable energy is generally redirected from a given flaw size at higher frequencies than at lower frequencies. An important consideration when choosing an inspection frequency is the sound beam attenuation in the material.

Empirical proof of the validity of the operating parameters was accomplished by setting the proper test parameters and inspecting special test pieces. The special test pieces were designed to evaluate each particular operating parameter. Each special test piece was inspected with the proper values, and then inspected again with an improper value. See Figures No. 7 and 8 A. The results of this test are listed and discussed below:

A. Incident Angle (α) for the Transmitted Beam

Angles at each end of the angular region for angle (α) were used for comparison with the test conducted using an angle (α) equal to 23.5°. A constant amplification was used; therefore, the amplitude of the redirected energy was indicative of the power transmitted into part and the efficiency of energy redirection by the interface. The amplitude of the redirected energy was lower at each end of the angular region than at the optimum angle (23.5°).

B. The Separation Distance and the Water Path of the Search Units in the Delta Configuration

The distance separating the search units was set for insufficient penetration into the material. Test holes at the bottom of the part were not detected. All test holes were detected with the proper separation distance.

C. Transmitter Beam Diameter

With the proper spacing of search units, a transmitter search unit having an insufficient beam diameter was used to inspect the test piece. Test holes near the top and bottom surfaces were not detected. Since the only parameter change was beam diameter, it is valid to state transmitter beam diameter as an important operating parameter. This parameter insures thorough coverage of the weld zone.

D. Receiver Search Unit Size

With the correct operating parameters, several Delta inspections were conducted. The receiver search unit size was varied for each inspection. All modes of redirected energy were detected with the largest receiver. Only the reradiated energy was detected with the smallest receiver. The degree of flaw information collected was directly proportional to the size of the receiver's effective region of capture. Therefore, it is important to select a receiver search unit having an adequate region of capture to collect the desired modes of redirected energy.

E. Test Frequency

Test frequency was varied from 1.0 MHz to 10.0 MHz with the proper parameters for Delta inspection. A weld panel containing various natural defects was used for the test. At 1.0 MHz, only the gross defects were detected. At 2.25 MHz the number of defects detected increased; however, the greatest number of defects were detected at 5.0 MHz. Attenuation of the ultrasonic energy at 10.0 MHz caused the test sensitivity to decrease rapidly. Defects near the surface were detected at 10.0 MHz, however, as the depth increased below 0.08", defect detection became erratic and difficult to repeat.

3.0 Test Procedure

3.1 Test Configurations

The basic Delta configuration is shown in the sketch in Figure No. 10A. Each important factor and parameter of the Delta configuration is labeled and identified on the sketch. All test configurations were variations of the basic Delta concept. Six configurations of the Delta were evaluated, each of which is listed below:

A. The basic Delta configuration, Figure No. 10A.

B. The Duo-Delta, two stationary transmitters and one stationary receiver, Figure No. 10B.

C. The basic Delta with an oscillating receiver, Figure No. 11.

D. The basic Delta with an oscillating transmitter, Figure No. 12.

E. The Duo-Delta with an oscillating receiver, Figure No. 13.

F. The Duo-Delta with dual oscillating transmitters, Figure No. 14.

The Delta Technique is a transmit/receive inspection method. A primary consideration for this type of testing is the net loop gain of the transmitter-receiver search unit combination. Because the transmitter function is to generate the incident energy beam, it is important to use the most efficient piezoelectric crystal for converting electrical energy to mechanical energy. Ceramic piezoelectric crystals, which are efficient transmitters, were used exclusively in this program. The receiver search unit serves only as a detector of ultrasonic energy, therefore, lithium sulphate crystals which are efficient mechanical to electrical energy convertors, were used. Any reference made to search units in the remainder of this text will carry the implication that all transmitter search units had ceramic elements and all receiver search units had lithium sulphate elements.

3.2 Test Description

All test data was recorded on facsimile recorders. The flaw information was recorded in a 1:1 relationship with respect to its location in the weldment or part. A Delta scan recording is similar to a conventional ultrasonic C-Scan recording.

3.2.1 The Basic Delta Configuration, Test A

The basic Delta configuration had one transmitter search unit and one receiver search unit. An acoustical lens was used on the receiver to increase the region of capture. A flat lens was used on the transmitter so the incident energy beam would be slightly divergent which increases the effective beam diameter. The setup procedure for the basic Delta is listed below: (Refer to Figure No. 10A)

A. The receiver search unit is placed normal to the part surface, directly over the flat end of the test hole in the reference standard. (The Delta reference standard shown in Figure No. 15 must be made from the same material and material thickness as the part being inspected.)

B. With the receiver in place, the transmitter is positioned perpendicular to the weld seam and then moved in and out to peak the response from the test hole. The angle of incidence for the transmitted beam is 23.5° in steel.

C. Test sensitivity was set by two methods. The second method was developed during the program and used exclusively from that point.

Method 1 - The instrument sensitivity is set for an 80% full scale deflection signal for the ultrasonic indication from a 5/64" diameter flat bottom hole in the reference standard.

Method 2 - A decibel (dB) attenuator is placed in the receiver line. With 20 dB attenuation in the line, the instrument sensitivity is set for an 80% full scale deflection signal for the ultrasonic indication from the 5/64" diameter hole. This method allows any sensitivity level to be selected by referencing a known attenuation value to an amplitude level established from a single test hole size.

3.2.2 Duo-Delta Configuration, Test B

The Duo-Delta configuration had a single, stationary receiver search unit and two fixed transmitter search units. This test setup was the same as for the Basic Delta, although each transmitter had to be positioned separately. The sound travel path for each transmitter was identical. Two transmitters positioned on opposite sides and perpendicular to the weld seam prevented a gross defect from blocking the rest of the weld from transmitted shear energy. Sensitivity was set for this test using Method 2.

3.2.3 Basic Delta Configuration with an Oscillating Receiver, Test C

This test setup was the same as for the Basic Delta. The receiver search unit was positioned at the mid-point in the excursion path to insure that the effective receiver coverage was centered about the prescribed intersection in the material. Flaw data recorded in this test represents the total flaw information collected during the complete excursion cycle of the receiver search unit. Test sensitivity was set according to Method 2 with the receiver at its mid-excursion point.

3.2.4 Basic Delta Configuration with an Oscillating Transmitter, Test D

Setup procedure for this test was identical to Test A. The transmitter search unit was placed at the mid-excursion point during setup procedures. Transmitter excursion caused the transmitted shear beam to scan above and below an imaginary line established by the propagation path of the fixed transmitted shear beam. Thus, effective beam diameter has been increased.

Flaw information recorded in this test is representative of the flaw content within the region of capture of the receiver search unit. This flaw information was recorded with respect to the receiver position. A mechanical motion for increasing effective coverage of the weld thickness was evaluated in this test. A small diameter transmitter search unit replaced the large diameter unit required for inspecting the same weld thickness with the basic Delta configuration.

3.2.5 Duo-Delta with an Oscillating Search Unit, Test E

This test procedure was identical to the dual Delta setup in Test B. The receiver was fixed at the mid-excursion point for setup and then shuttled for testing. Flaw information recorded in the test was very similar to that recorded in Test C.

3.2.6 Dual Oscillating Transmitter Configuration, Test F

Positioning fixtures for this test were designed so the transmitted shear beam from each transmitter would have symmetrical motion about the receiver axis. The transmitters were positioned at mid-excursion for setup. Each transmitter was positioned separately. Matched transmitter search units were used for the test. Test sensitivity was set by Method 2. Flaw information recorded for this test was the same as that recorded in Test D. The primary concern was the effective thickness coverage achieved using smaller diameter transmitter search units. Transmitter shuttle speed was varied to determine the effects of speed with respect to defect definition. The assembly shown in Figure No. 16 was attached to the C-Scan bridge and scanned in the conventional manner used for making C-Scan recordings.

4.0 Test Results

One of the objectives of this study was to determine a practical method of providing permanent records for the ultrasonic weld inspection. An Alden Facsimile Recorder was used to display the Delta test results. The receiver search unit position is used for referencing flaw location because the reradiated energy exits directly above the flaw. Although some depth information is present in the redirected energy, depth information is not readily evident in a Delta scan recording.

Selected radiographs of the weld panels are shown with the respective Delta scan recordings. The radiographic results are included to illustrate specific capabilities and limitations of the Delta Technique. Comparison of the radiograph, Delta scan and destructive test results illustrates what each test method will detect reliably.

4.1 Test A - Basic Delta

Delta scan recordings made with the basic Delta configuration are shown in Figures No. 17, 18, 19, and 20. The various weld panels inspected were in a thickness range from 0.750 inches to 1.25 inches. The weld configurations were double vee butt welds. Some of the panels used in the program were fabricated as radiographic qualification standards and contained gross defective conditions. The defect content in these welds included: slag, porosity, cracks, lack of penetration, and lack of fusion.

Each Delta scan recording has the weld zone identified. Areas from which destructive test samples were taken are marked on the respective recordings.

Results of the Delta tests in which the frequency was varied are shown in Figure No. 21. An exploratory Delta inspection was made of a tee weld configuration using Delta operating parameters for butt weld inspection. The frame and flange of the tee weld were 1.0 inch thick. Parameters for butt weld inspection were used with the separating distances set for penetration to the weld zone. The inspection was conducted from the top of the tee and at 5.0 MHz. Results of the tee weld inspection are shown in Figure No. 22. Weld zones are outlined on the Delta scan recording and the area of destructive analysis is noted.

4.1.1 Discussion of Test Results from Test A

Test results for panels A, B, C, and D are shown in Figures No. 18 and 19. Panel A was radiographically clean and Delta test results agreed. Test holes drilled in the center of the weld zone serve as markers to indicate the weld region and the relative indication sizes for different size reflectors. Weld panel B was supposedly good and was to have been used as the reference weld for comparison with bad weld. The radiograph showed large porosity groups in the weld but otherwise, no detrimental defects. Delta scans indicated a gross defect condition throughout the weld zone. Destructive tests performed on the sample revealed gross lack of fusion and areas containing slag inclusions. Weld panels B and D were samples of unacceptable weld. Radiographic and Delta test results agreed completely for these samples.

Sample No. S was chosen for a detailed discussion of the Delta weld inspection versus conventional weld inspection methods. Test results shown in Figure No. 20 include a radiograph, a conventional 60° angle beam test, and a Delta scan. The weld defects were slag and lack of fusion. Sensitivity for the ultrasonic tests was identical. Each test had an 80% full scale deflection signal for the ultrasonic response from a 3/64" diameter, flat reflector. These tests were made after the weld crown had been ground flush. Inconsistencies in the weld were not

recorded using the conventional angle beam inspection. Ultrasonic signals were received from the large slag inclusion; however, the amplitudes of these signals were below the recorder "write" level and were not displayed. The larger defects were detected with the conventional angle beam test after the initial sensitivity level was doubled. Delta weld inspection at the initial sensitivity revealed a defective condition throughout the weld zone. The radiographic test results correlated very closely with the Delta results except for the area at point A. The radiographic indications were intermittantly visible throughout the weld but some of these were faint and difficult to evaluate. Much detail has been lost in the photographic reproduction of the radiograph, although the defect pattern can still be distinguished.

Destructive test results shown in Figure No. 28A confirm the Delta test results for point A. Elsewhere in the weld, Delta tests correlated closely with radiographic examination; nevertheless, a destructive test specimen was taken from the area containing the large slag inclusion. Results of this test are shown in Figure No. 28B.

This series of tests have compared three methods for weld inspection. Test sensitivity for ultrasonic and radiographic weld inspection was compared by evaluating the final result. Comparison of the ultrasonic test sensitivities was made by setting each test for equal response from the same size reflector and then evaluating the final results. Of the three test methods, the conventional angle beam test was the least sensitive to the type defects in this weld. The Delta test detected the largest number of inconsistencies in the weld; however, identification of the weld defects was determined more accurately by radiography. Delta inspection of this weld panel was accomplished at a rate of 50 feet per hour.

Most of the weld panels were inspected in the "as welded" condition with no preparation of the weld bead. Weld panels J, K, and L were the radiographic standards and had the weld bead ground flush during fabrication. Definition of weld flaws in the Delta scan recordings was consistently better for the weld panels with a prepared weld bead; however, acceptable sensitivity was achieved in the "as welded" condition. Several varying steps of weld preparation were made to determine which weld bead condition was most suitable for Delta weld inspection. A flush weld bead was the most desirable, but a "blended" weld bead was satisfactory. A "blended" weld bead configuration has a small flank angle and a large toe radius, see sketch in Figure No. 23. Weld bead blending was accomplished by grinding the weld bead and blending the crown into the parent metal so that sharp surface changes did not occur anywhere along the weld seam. In the vicinity of the weld seam, an abrupt change in the metal surface becomes an interface which causes the incident energy beam to be redirected. Spurious indications were detected in all cases where an abrupt surface change occurred. The increase in defect definition and test sensitivity

is evident in the Delta scan recording shown in Figure No. 24. Note the small improvement obtained between the "blended" weld condition and the "flush" weld bead condition, as compared with improvement between the "as welded" weld bead condition and the "blended" weld bead condition. Radiographic tests performed between each weld bead preparation insured that no defects had been removed during the grinding operation.

Test results for the tee weld inspection indicated a gross defective condition in one of the weld seams. A destructive test conducted in the suspicious area revealed extensive cracking. This crack was parallel to the top of the "tee". Destructive test results are shown in Figure No. 29.

4.2 Test B - Duo-Delta (Stationary Search Units)

Delta scan recordings made with the dual transmitter/single receiver Delta are shown in Figure No. 25. Selected recordings of the weld panels are shown in these figures to illustrate typical results obtained with this test method.

4.2.1 Discussion of Test Results for Test B

Maximum defect definition and test sensitivity was obtained with the Duo-Delta configuration. Radiographs of the weld panels are included in Figure No. 25. The radiograph was placed directly above the respective Delta scan so the defect definition could be compared.

4.3 Test C - Basic Delta with an Oscillating Receiver Search Unit

Test results for this test are not included.

4.3.1 Discussion of Test Results for Test C

An oscillating receiver search unit collected flaw information along the entire receiver excursion path. The net result for this Delta configuration was an agglomeration of defect information superimposed about a single point on the display. Any advantage gained from this method of inspection was offset by the difficulty encountered in displaying the flaw information in some intelligent form.

4.4 Test D - Basic Delta with an Oscillating Transmitter Search Unit

Results of the oscillating transmitter Delta configuration are shown in the Delta scans of Figure No. 26. The major flaw in each weld panel was shown for comparison with the Basic Delta scans in Figure No. 17 and the Duo-Delta scans shown in Figure No. 25. Radiographs of the weld panels are included in Figure No. 25.

4.4.1 Discussion of Test Results for Test D

Defect indications are distorted and reveal less detail than the fixed Delta scans; however, these recordings were made with a small diameter transmitter search unit for the purpose of evaluating the oscillating motion. The defect definition obtained with this Delta Technique correlates closely with the other Delta scans and the radiograph. This method of Delta inspection was evaluated for use in the inspection of thick welded structures where the required size for a fixed transmitter was prohibitive.

4.5 Test E - Duo-Delta with an Oscillating Receiver Search Unit

Test results from this test are not included for the same reasons that results were not included for Test C. Discussion of these tests is the same as for Test C.

4.6 Test F - Duo-Delta with Dual Oscillating Transmitter Search Unit

Test results for the dual oscillating transmitter Delta configuration are not shown. The test results for this test are nearly identical with those for Test D. Dual transmitters deliver more energy to the weld zone thereby increasing the test sensitivity as compared with the single transmitter configuration used in Test D.

4.6.1 Discussion of Test Results for Test F

Defect elongation was held to a minimum in this test by using a "selective gating" technique. A selective gating technique refers to the time interval in which flaw information will be recorded. In the discussion of the various modes of redirected energy, the time of travel within the material for each energy mode was identified; therefore, by selectively gating or accepting discrete time periods, a single energy mode can be used for recording flaw information. This practice is referred to as selective gating.

4.7 Destructive Test Results

Several of the expendable weld samples were sectioned to reveal the actual defect content. Results of the macroscopic examination of these weld samples are shown in Figures No. 27, 28, and 29. The various areas from which the destructive test sections were cut are located on the respective Delta scan recordings.

II. CONCLUSIONS AND RECOMMENDATIONS

1.0 Conclusions

Analysis of the Delta phenomena shows three classes of redirected ultrasonic energy resulting from an interaction between the incident energy beam and an interrupting interface. Utilization of all three classes of energy make the Delta Technique relatively insensitive to defect orientation. The three classes of redirected energy were identified as (1) reflected, (2) mode converted, and (3) reradiated. Each class of redirected energy has a distinctive characteristic that makes it easy to identify in most inspection setups. Although an extensive study relating defect depth with a programed analysis of each discrete wave characteristic was beyond the scope of this program, the potential for determining defect depth should be considered for later studies.

The primary goal of this program was to thoroughly analyze the Delta Technique and develop the parameters which would allow this concept to be used as a practical weld inspection method. This has been accomplished. Parameters which govern the Delta operation have been identified and defined. See Table I. Successful weld inspection has been accomplished by using the parameters specified for the particular weld material, thickness, and configuration. A facsimile recording of the test results provided a permanent record which was easily interpreted and correlated directly with the radiograph. Delta scan recordings can be interpreted as easily as X-ray film.

Randomly oriented defects ranging from vertical cracks to laminar inclusions were consistently detected with the Delta inspection technique. Definition of planar and single spherical defects was excellent. Groups of porosity were not defined individually but instead, were defined as defective areas representative of the group. The test results obtained with the Delta Technique are not like the radiographic image reproductions; therefore, planar defects cannot be identified as cracks, lack of fusion, or lack of weld penetration. Regardless of the defect type, no defects detrimental to the weld integrity were undetected by the Delta inspection when performed with the proper operating parameters.

Delta scan facsimile recordings showed excellent correlation with radiographic test results and, in instances, detected defects missed in the radiographic test. A prototype handheld Delta probe was used to inspect a weld panel representative of the welds being used on submarine hulls. Test results were marked on the weld panel with a grease pen as the operator manipulated the probe. These results correlated perfectly with the Delta scan recording. Destructive tests confirmed the existence of defects in the weld at the indicated points. Therefore, either manual or automatic Delta weld inspection will provide the same test results. Weld thicknesses ranging from 0.750 inches

to 1.750 inches were inspected successfully. Preliminary test conducted on thicker welds, approximately 4 inches, have shown encouraging results. The 4 inch welds are not part of this program but are mentioned to give the reader an indication of the material thickness range where Delta weld inspection has been effective.

Evaluation of the Delta Technique versus conventional weld inspection methods has established four facts:

(1) Delta weld inspection will detect weld inconsistencies at least as well as radiographic techniques.

(2) Delta weld inspection can be accomplished in less time than radiographic weld inspection and without the accompanying radiation hazard.

(3) At the present time, radiographic techniques identify weld defects more accurately than the Delta Techniques.

(4) The Delta Technique is not defect orientation sensitive and conventional angle beam inspection is orientation sensitive.

In view of these facts, the most promising use of the Delta weld inspection would be for rapid acceptance of good weld. Critical evaluation of the defective weld areas could be accomplished with several nondestructive testing methods, either radiographic or ultrasonic.

2.0 Recommendations

Although the Delta Technique is equally effective in either the manual or automatic operation, an automatic scanning system is recommended as the primary method for employing the Delta as a weld inspection tool. Advantages of an automatic Delta weld inspection system include: (a) automatic weld scanning, (b) faster weld inspection, and (c) permanent records of the inspection. Two types of permanent records are available with the Delta Technique: (a) strip chart or line-event recordings, and/or (b) facsimile recordings like those shown in this report. Each type of recording has definite advantages. Both types of recordings and the accompanying systems are discussed in broad scope in the following paragraphs.

Facsimile recordings are "X-Y" plan view plots of the weld and the defect location. An automatic weld inspection system utilizing this data display requires a mechanical scanning fixture to follow the weld seam and translate the Delta motion directly to "X" and "Y" placement of flaw information.

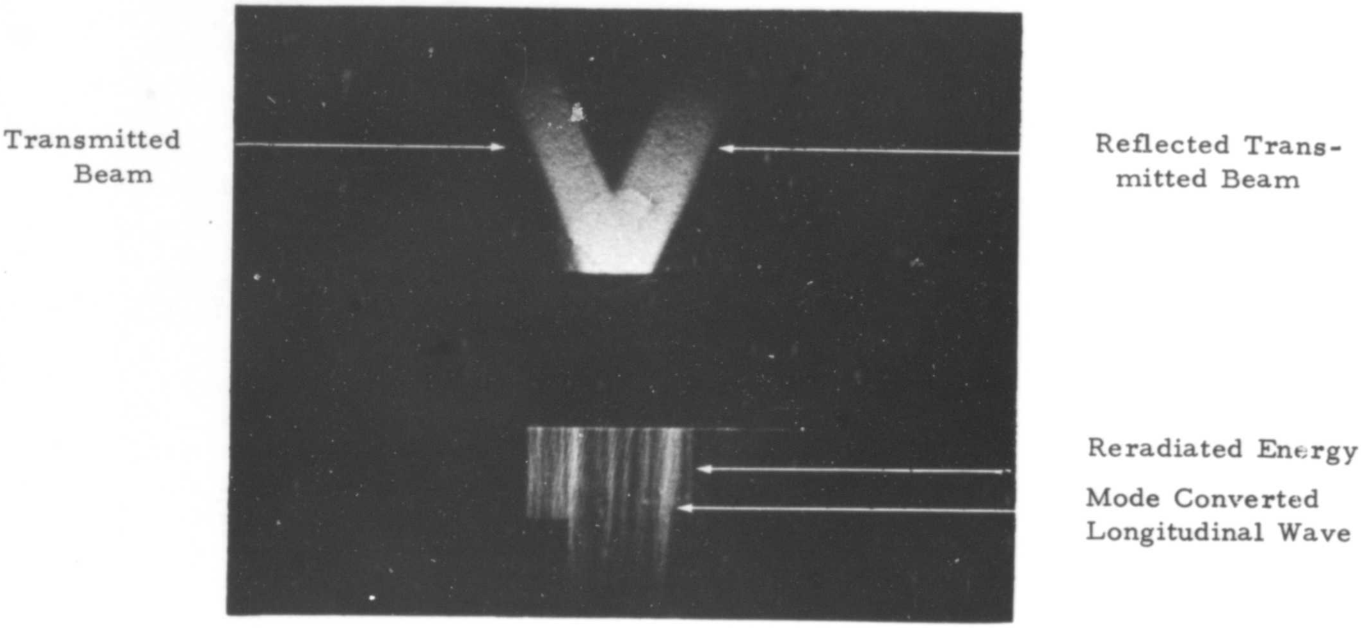
This system would consist of conventional flaw detection instrumentation, an automatic scanning fixture, a Delta fixture, a remote facsimile recorder, and conventional search units.

Strip chart recordings are line-event plots of the weld length versus flaw location. This type of data display locates the flaw along the weld length and records the flaw amplitude. The automatic positioning fixture for this system would be a weld seam following device that scans the Delta fixture perpendicular to the weld seam as it moves. This system would contain the same components as the system above with a strip chart recorder replacing the remote facsimile recorder.

Both of the automatic systems would have an operating parameter chart for weld configuration, material, and weld thickness. The chart would be established for the particular system from the general parameters developed in this program. Each system would have mechanical positioning controls for setting the proper parameters by dial indicators.

It is recommended that the Delta Technique for weld inspection be considered as a means for rapidly accepting good weld. The philosophy behind this recommendation is that rapid acceptance of good weld will reduce the cost of weld inspection. Where the weld is suspect, a more critical examination which employs different NDT methods can be used.

Although concentrated study of Delta inspection for the tee weld configuration was not within the scope of this program, an exploratory Delta inspection of a tee weld was conducted using the parameters developed for butt weld inspection. Results of this inspection were encouraging. We believe the initial success of the Delta tee weld inspection is sufficient to warrant consideration of the Delta Technique as an inspection method for the tee weld configuration and recommend that further evaluation of this application be made.



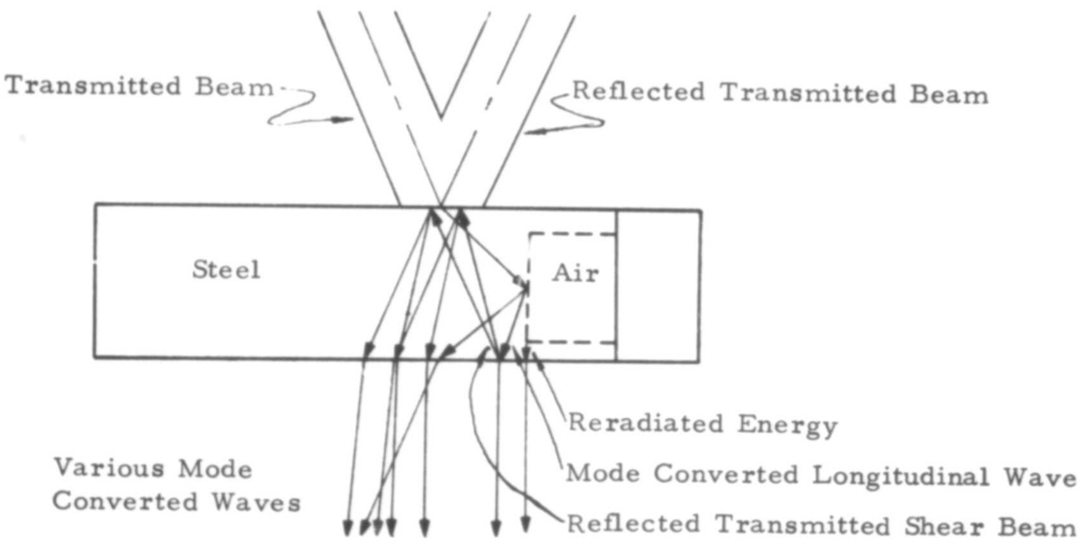


Figure 1. Schlieren Photo and Ray Analysis

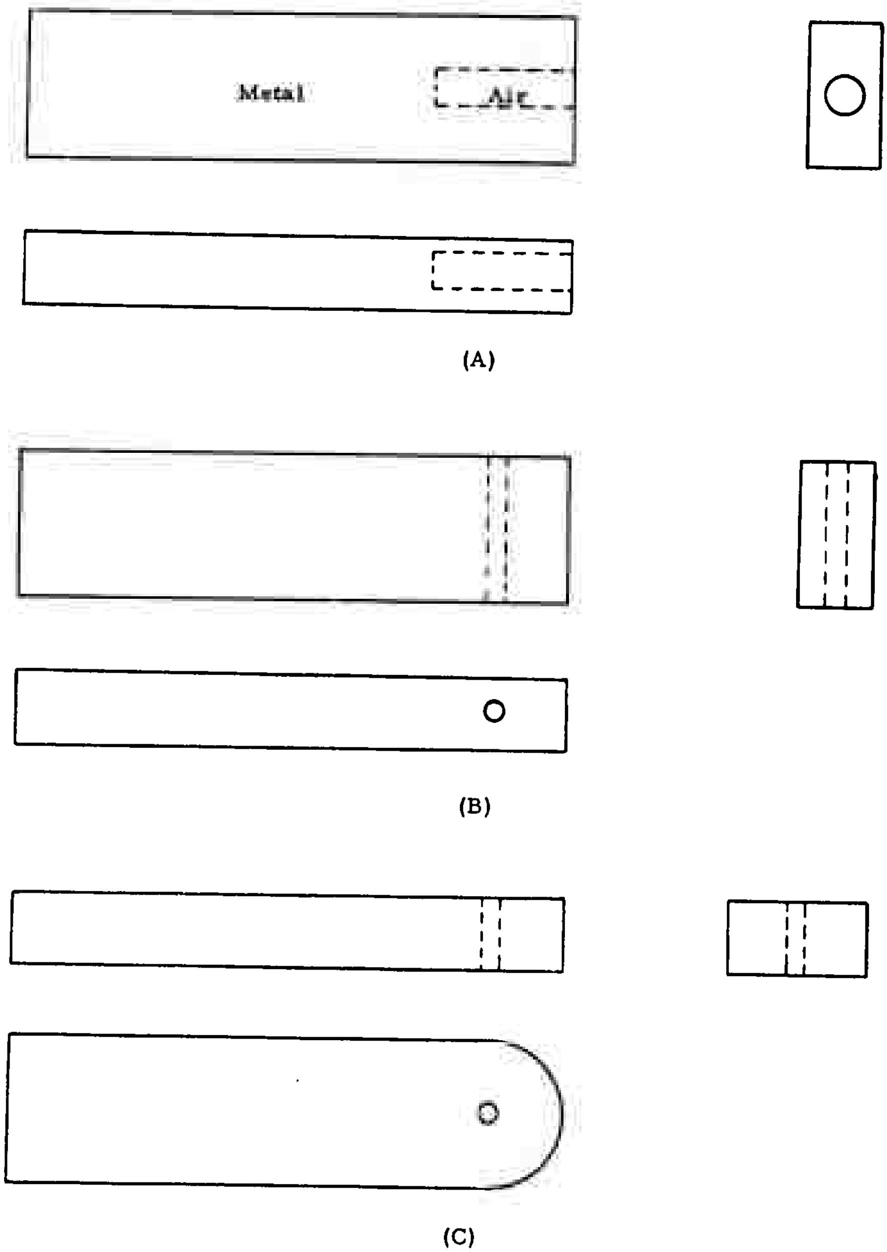
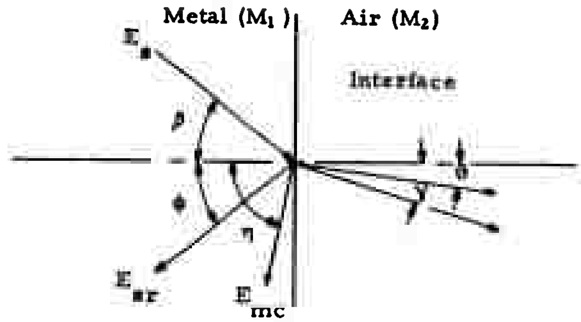


Figure 2. Test Models used for Analyzing the Delta Phenomena



Snell's Law

$$\frac{\text{Sin } \beta}{\text{Vel}(E_s)} = \frac{\text{Sin } \phi}{\text{Vel}(E_{sr})} = \frac{\text{Sin } \eta}{\text{Vel}(E_{mc})} = \frac{\text{Sin } \theta}{\text{Vel}(E_{st})} = \frac{\text{Sin } \gamma}{\text{Vel}(E_{lt})}$$

Since the E_{mc} becomes nonexistent when $\eta = 90°$, the angular region of β can be predicted by setting the range of η so $0 < \eta < 90°$. Therefore, β lies in the angular region defined as: $0 < \beta < \sin \dfrac{V_{(E_s)}}{V_{(E_{mc})}}$

E_s - Incident energy beam (shear wave in steel - $V_s = 3.23$ mm/μ sec.

E_{mc} - Mode converted longitudinal wave (longitudinal wave in steel, velocity - $V_l = 5.85$ mm/μsec.

E_{sr} - Reflected incident energy beam (shear wave, velocity is $V_s = 3.23$ mm/μsec)

E_{lt} - Longitudinal wave in air resulting from interaction of E_s and the interface, velocity in air, V_l (air) = 0.33 mm/μsec.

E_{st} - (nonexistent) Would be shear wave if M_2 would support shear energy propagation.

Figure No. 3. Predictions of Wave Behavior at Interface by Snell's Law

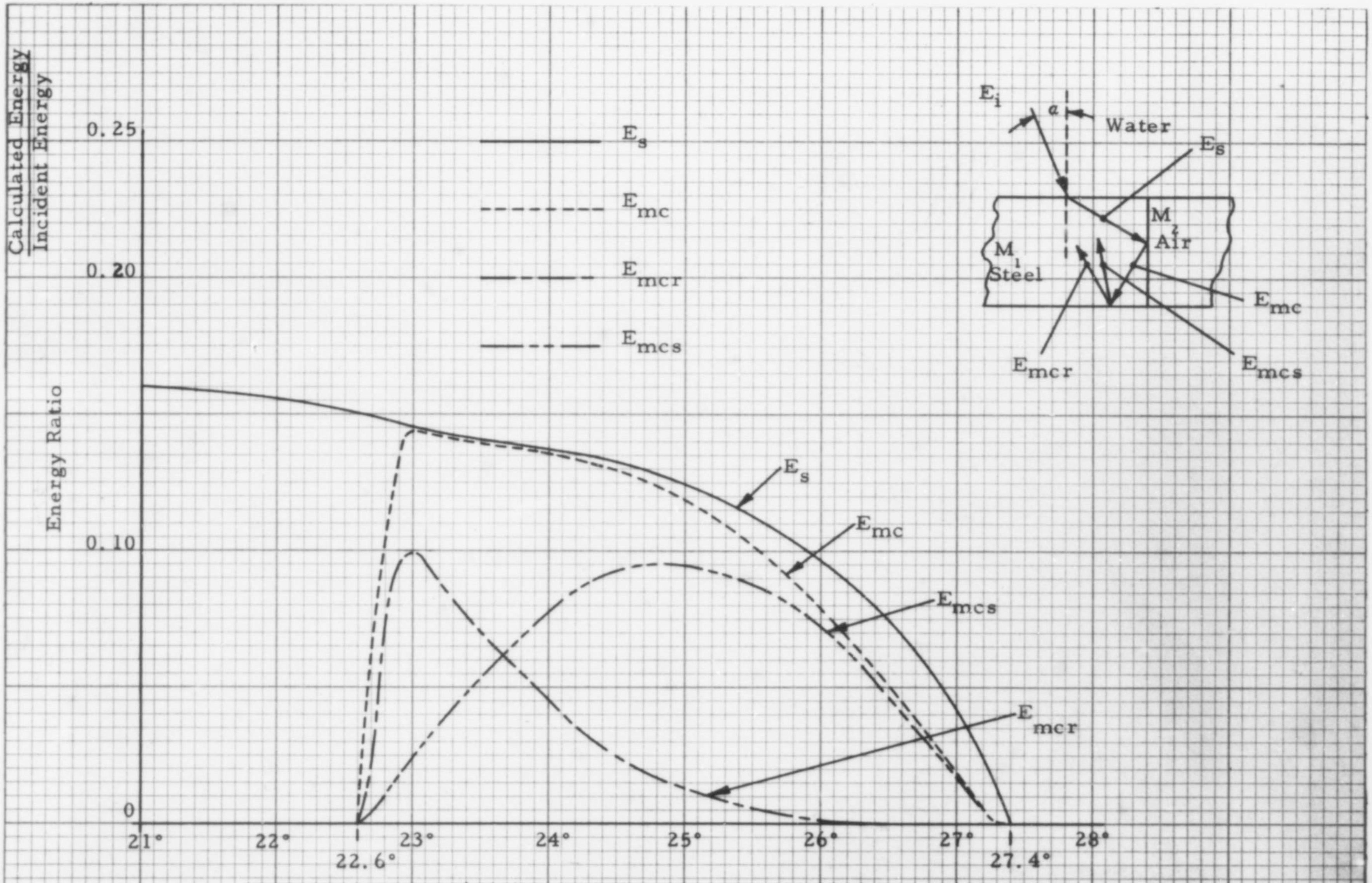


Figure No. 4. Angle of Incidence a of Longitudinal Energy E_i vs. Energy Partition at First and Second Mode Conversions

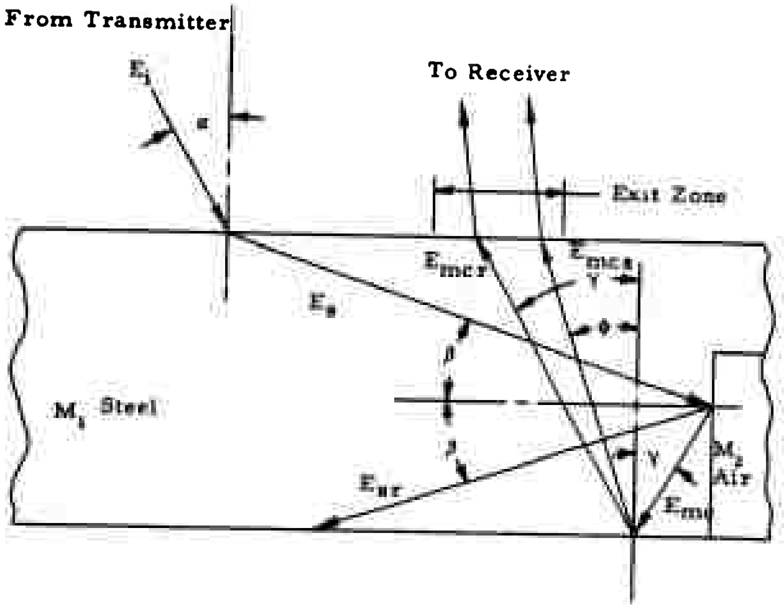


Figure No. 5. Ray Analogy of "Delta Configuration"

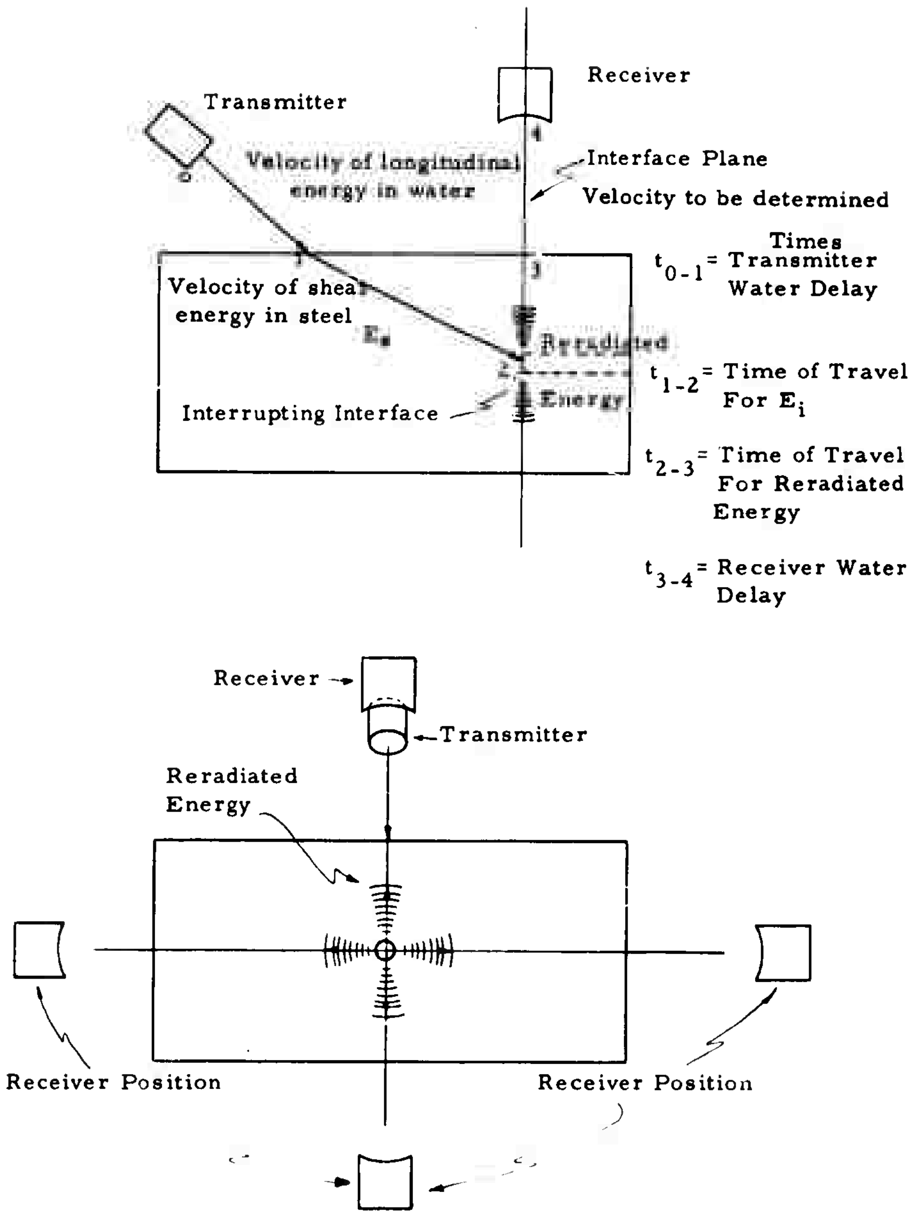
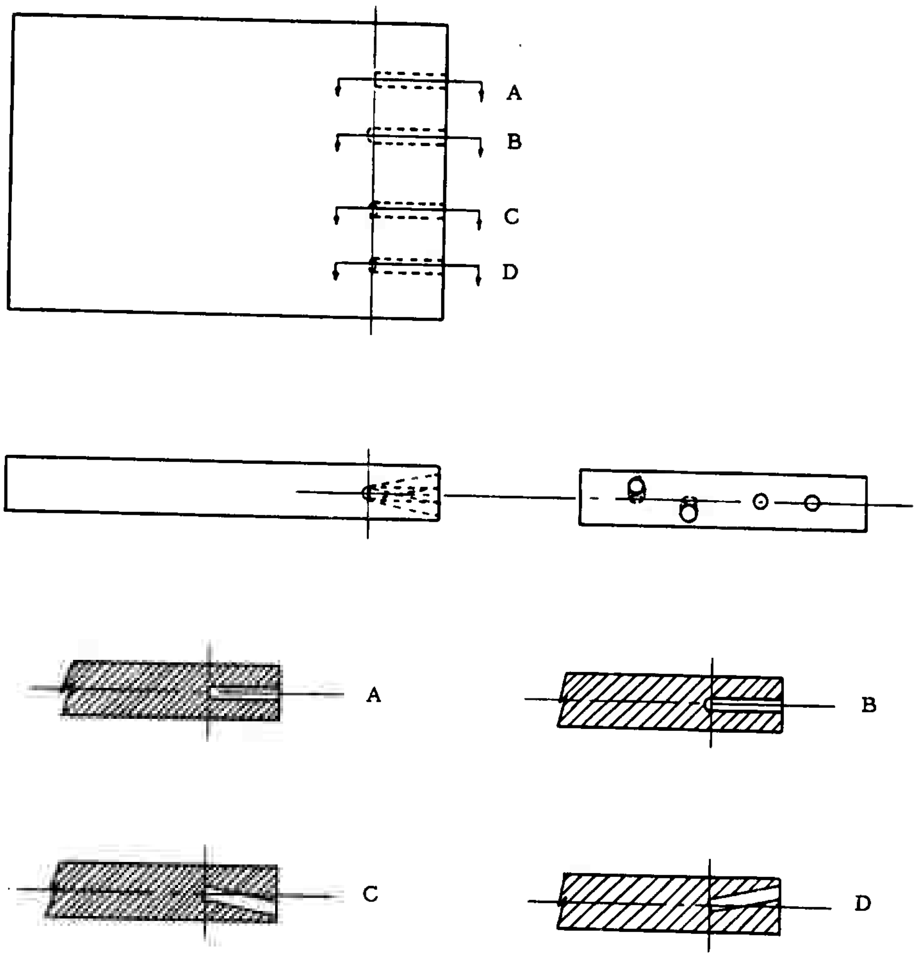
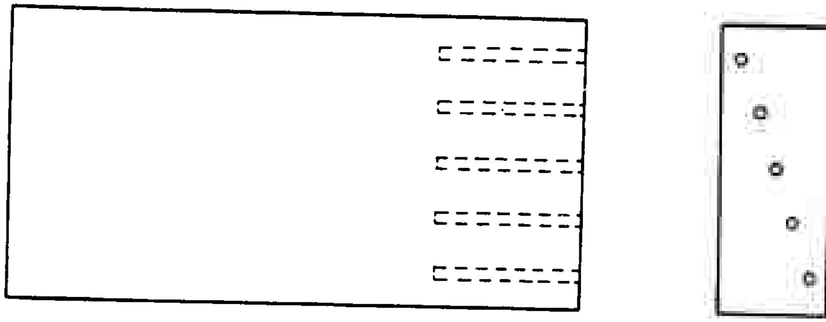


Figure No. 6. Method of Velocity Measurement for Reradiated Energy

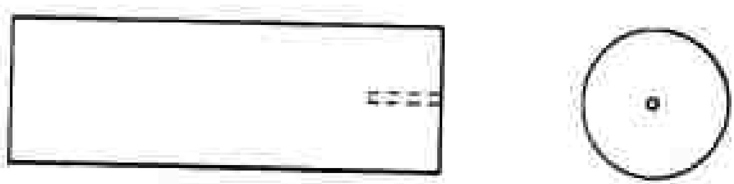


All holes are 5/64" diameter. The test sample is 0.750" steel plate.

Figure No. 7. Test Part Containing Reflectors of Various Shapes and Orientation Used to Verify Delta Operations

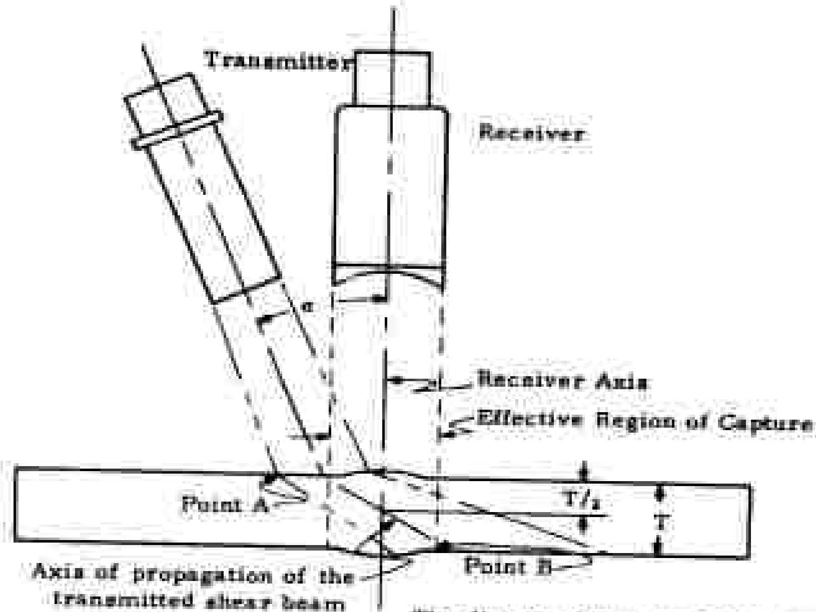


A



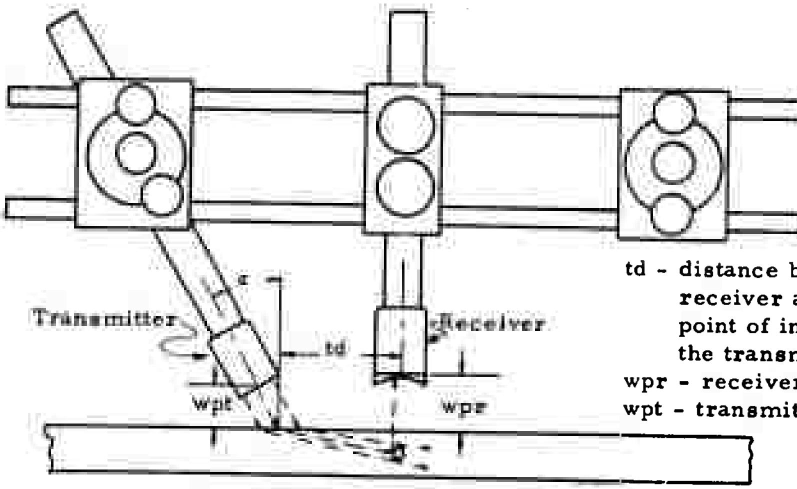
B

Figure No. 8. Test Pieces for Establishing Validity of Delta Operating Parameters



The distance between points A and B represents the vertical width of the receiver region. An effective beam diameter for a transmitter search unit is adequate if the weldment can be thoroughly inspected by moving the Delta so the receiver axis starts at points A and ends at point B.

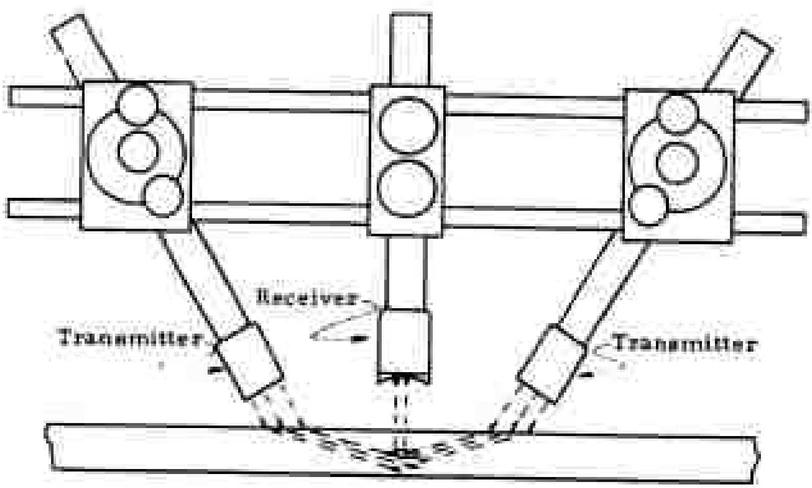
Figure No. 9. Beam Requirements for Proper Delta Operation



td - distance between the receiver axis and the point of incidence of the transmitted beam.
wpr - receiver water path
wpt - transmitter water path

Basic Delta Configuration

A



Dual Delta Configuration

B

Figure No. 10. Delta Test Configuration

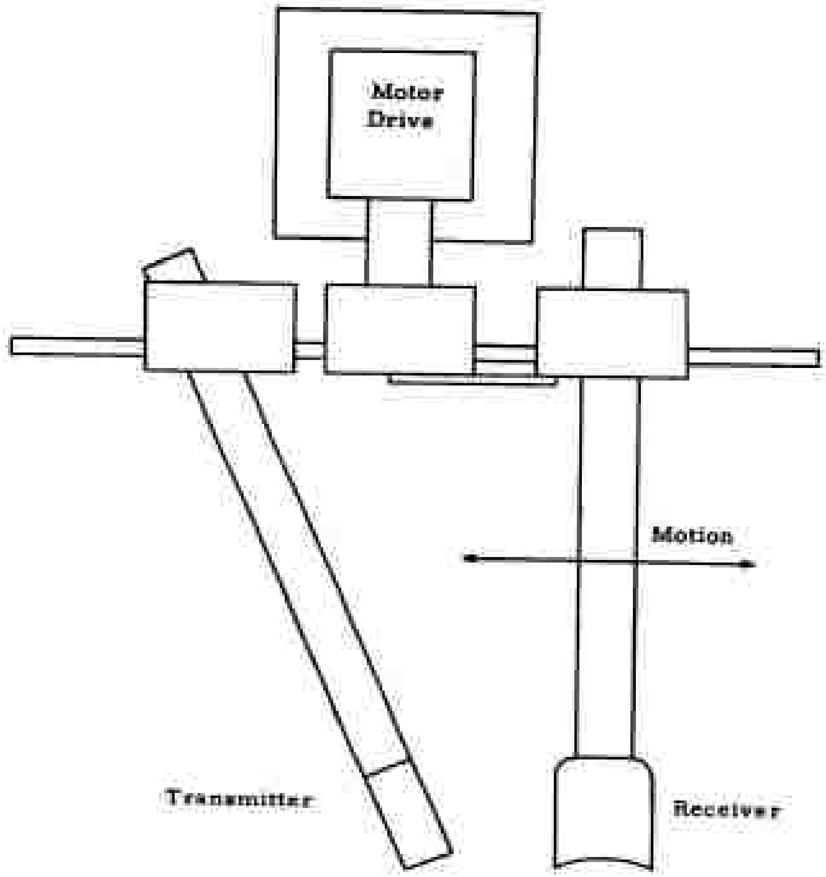


Figure No. 11. Fixed Single Transmitter/Oscillating Receiver Delta Configuration

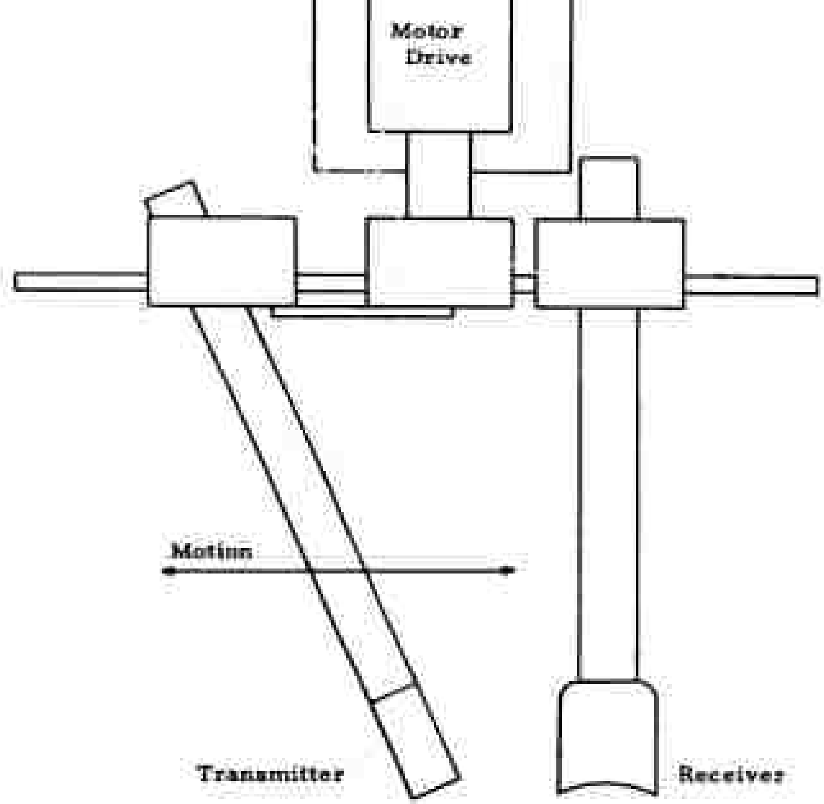


Figure No. 12. Single Oscillating Transmitter/Fixed Receiver Delta Configuration

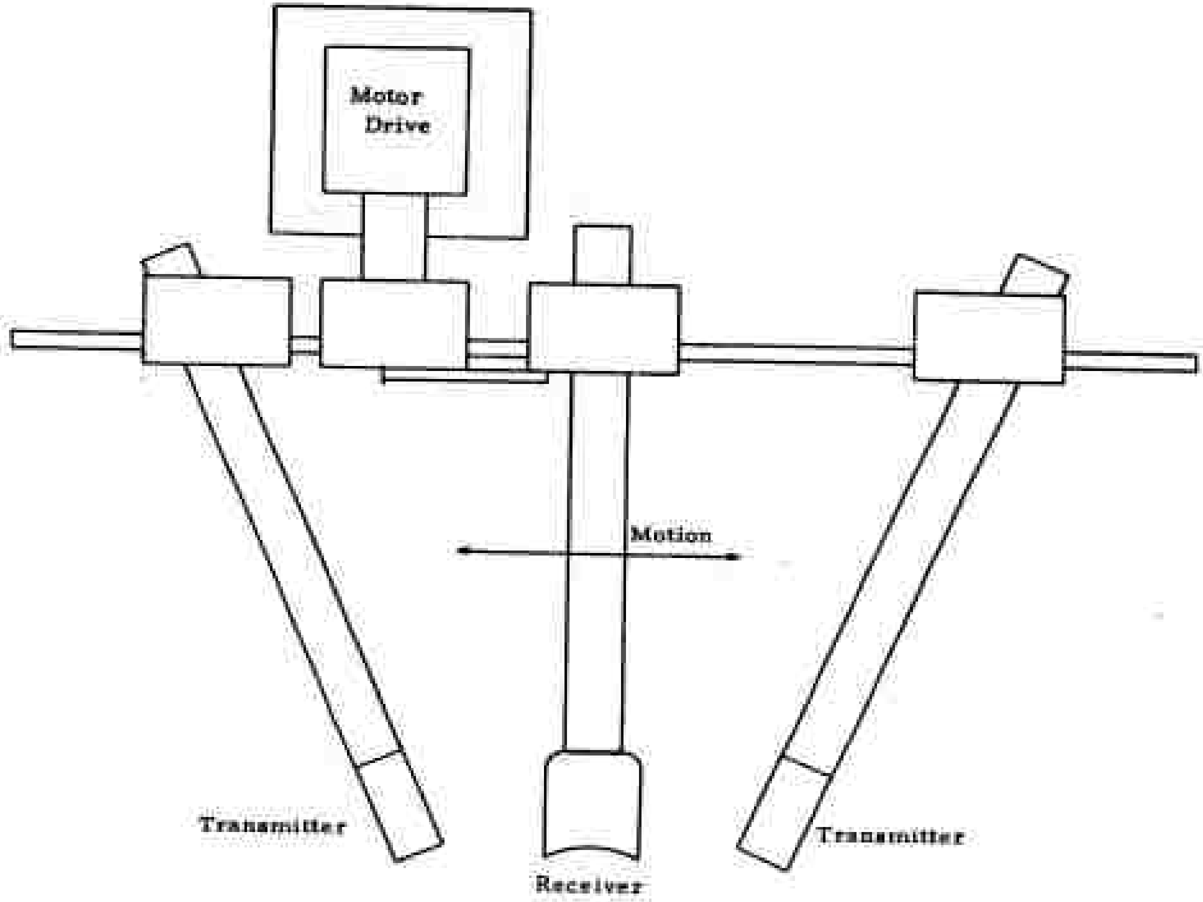


Figure No. 13. Fixed Dual Transmitter/Oscillating Receiver, Delta Configuration

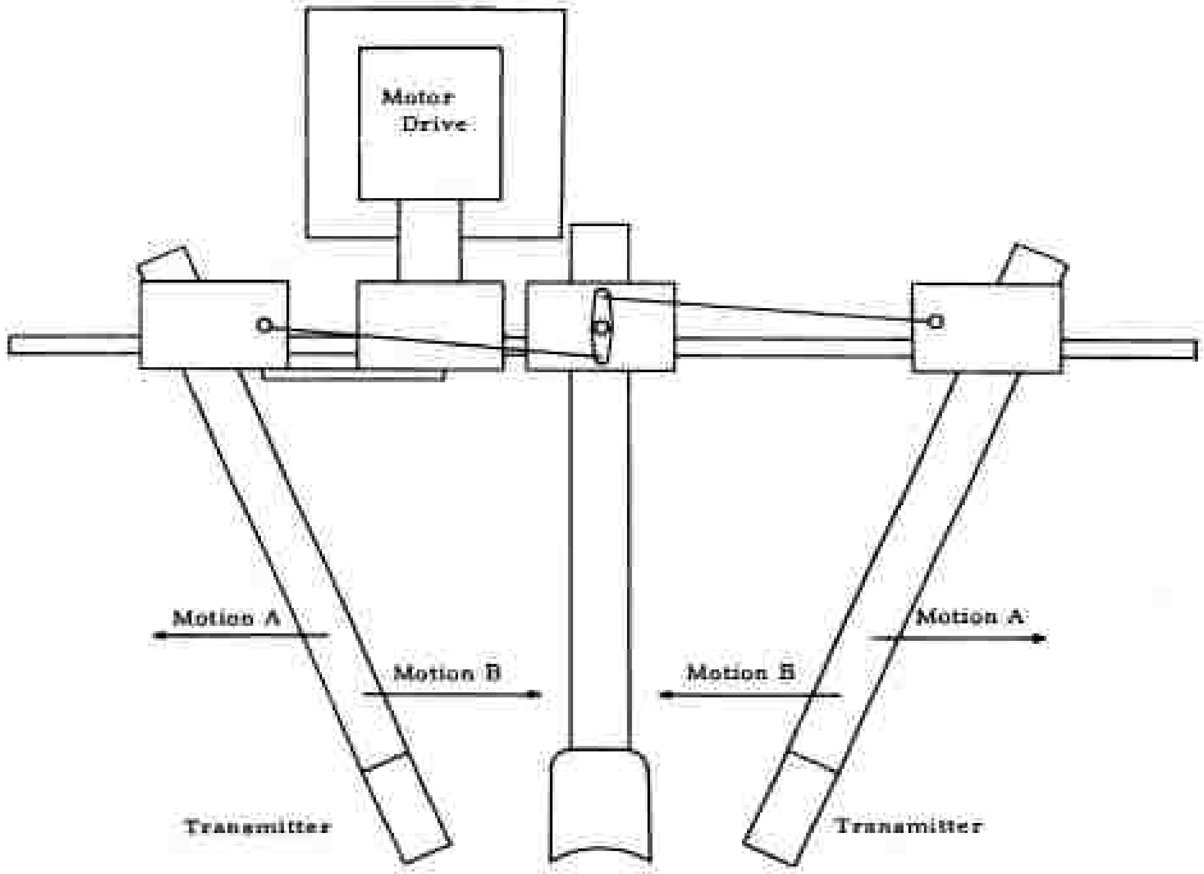


Figure No. 14. Dual Oscillating Transmitter, Symmetrical Shuttle Delta Configuration

A- 5/64" diam. Flat Bottom Hole
B- 1/8" diam. Flat Bottom Hole
C- 1/4" diam. Flat Bottom Hole

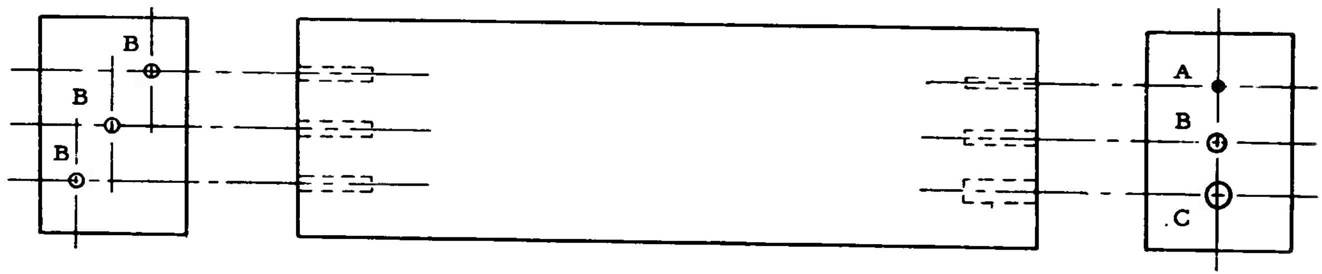


Figure No. 15. Delta Reference Standard

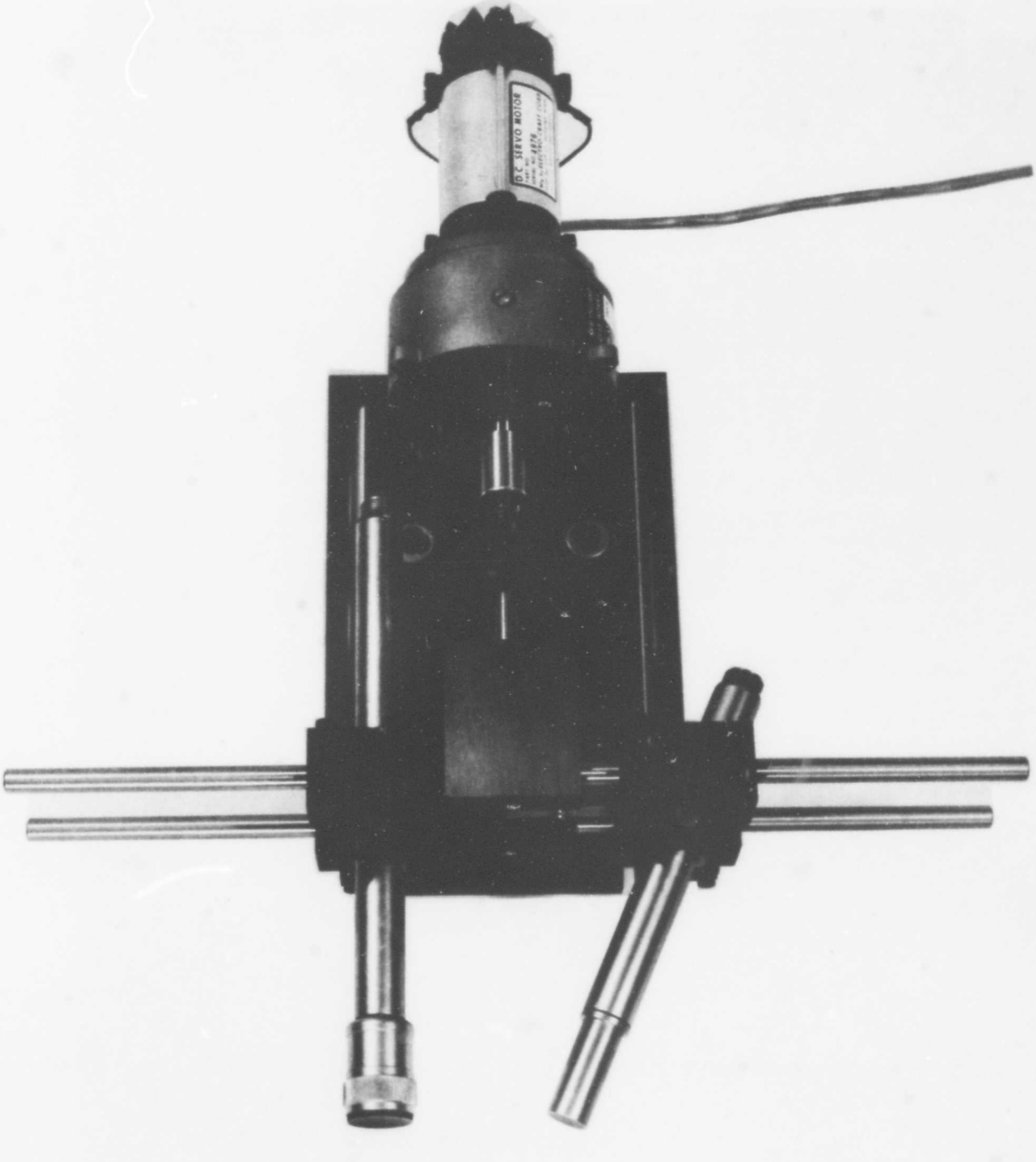
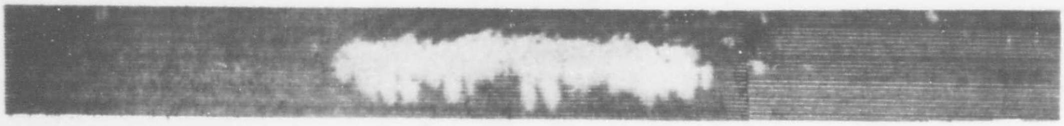
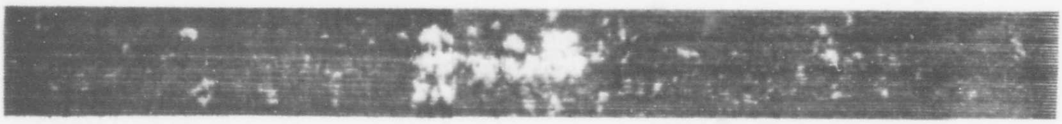


Figure No. 16. Delta Fixture of Oscillating Search Units

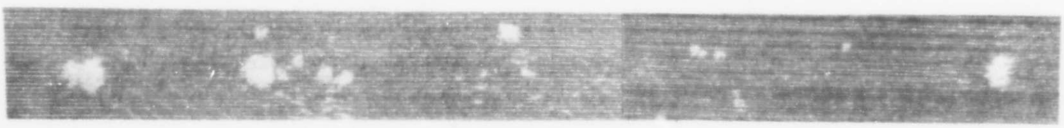


PANEL I

PANEL J



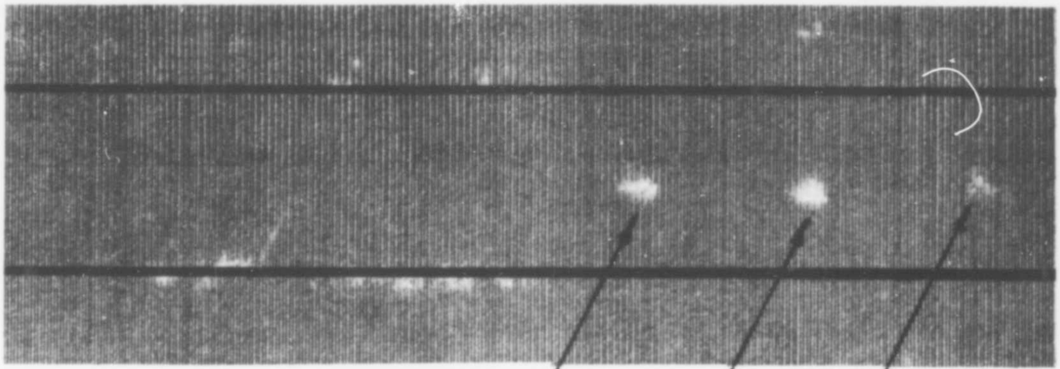
PANEL K



PANEL R

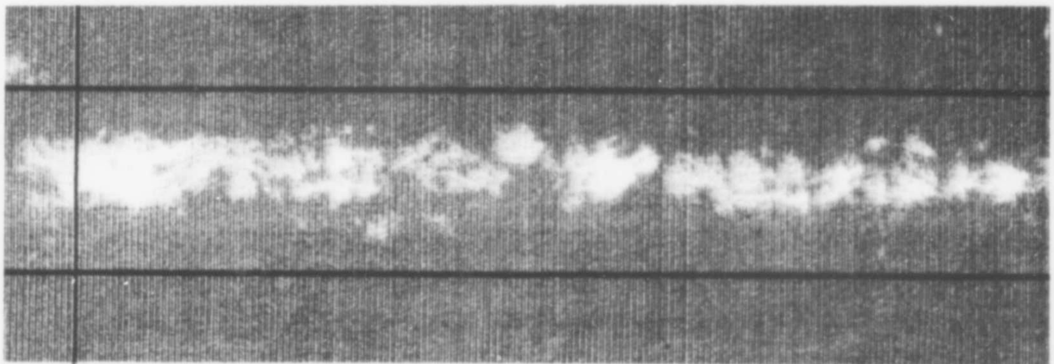
SINGLE RECEIVER / SINGLE TRANSMITTER DELTA RECORDINGS, $\alpha = 23.5°$

FIGURE NO. 17



Panel A

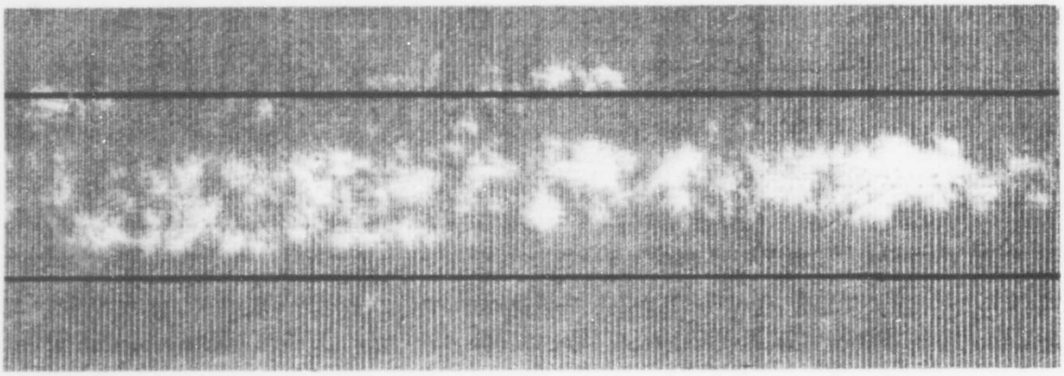
Defect Content: Clean



Panel B

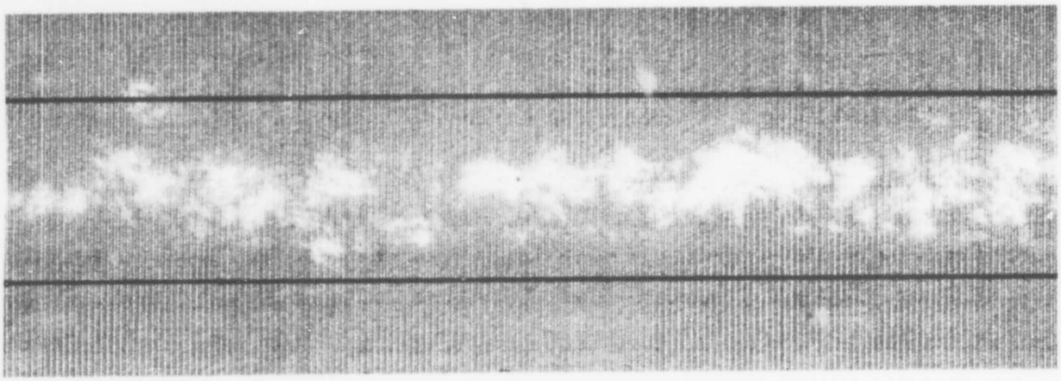
Defect Content: Porosity, Slag Inclusions, Lack of Fusion

Figure No. 18. Delta Scans for 1" Butt Welds



Panel C

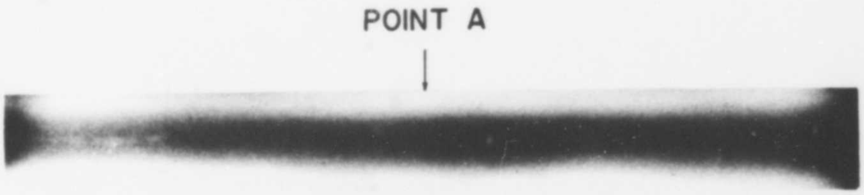
Defect Content: Slag Inclusions, Lack of Fusion



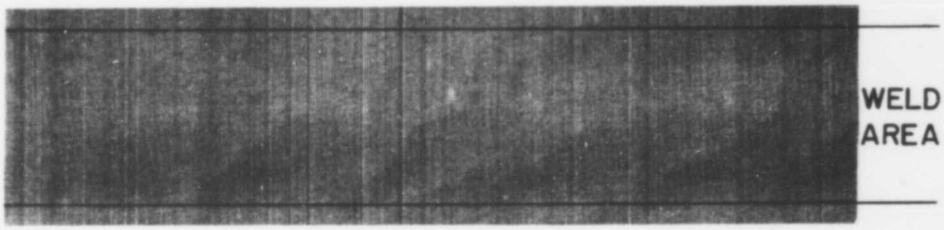
Panel D

Defect Content: Porosity, Slag Inclusions, Lack of Fusion

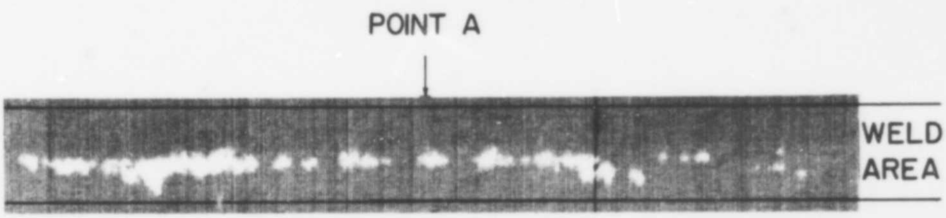
Figure No. 19. Delta Scans for 1" Butt Welds



RADIOGRAPH



60° SHEAR WAVE RECORDING

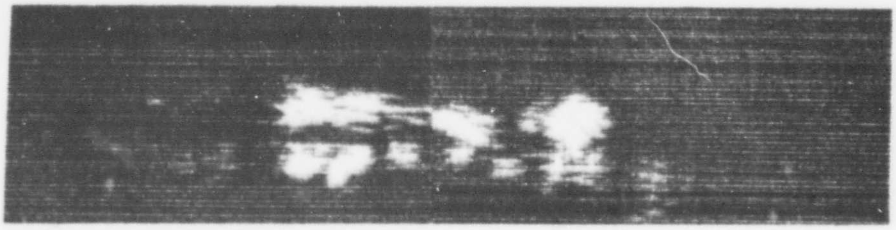


DELTA SCAN RECORDING

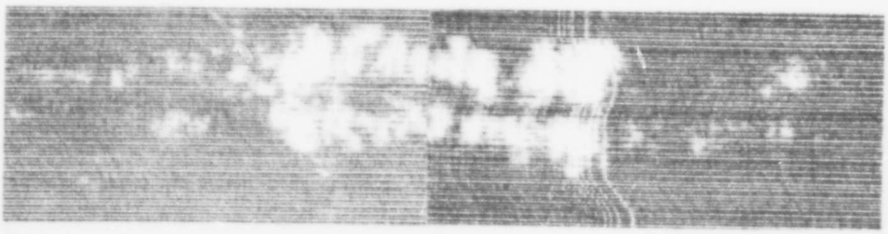
WELD INSPECTION RESULTS FOR PANEL S

FIGURE NO. 20

Panel K
1.0 MHz



Panel K
2.25 MHz



Panel K
5.0 MHz

Figure No. 21. Basic Delta Scan Recordings At Various Frequencies

$\alpha = 23.5°$

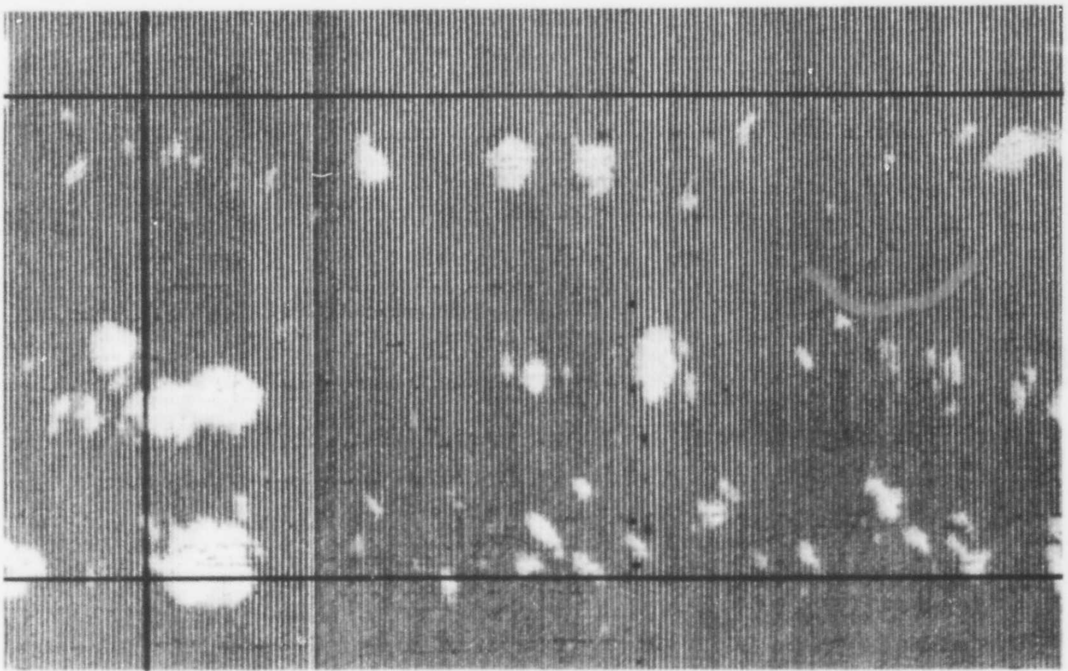


Figure No. 22. Tee Weld Delta Scan

R - Toe Radius

θ - Flank Angle

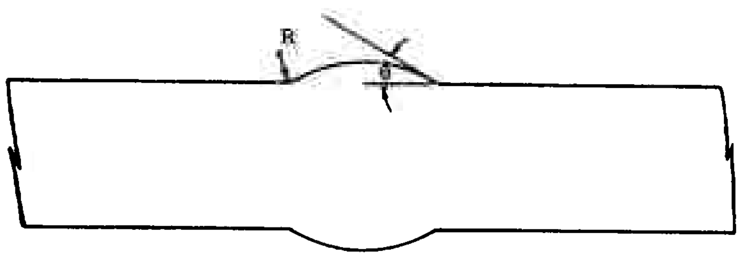
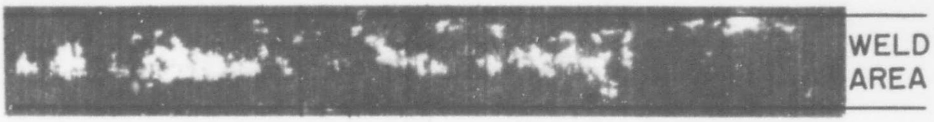
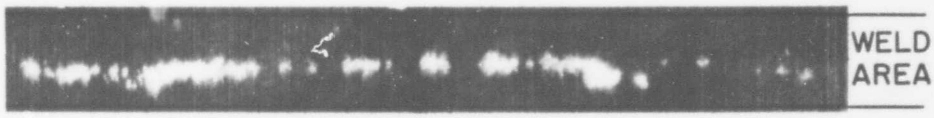


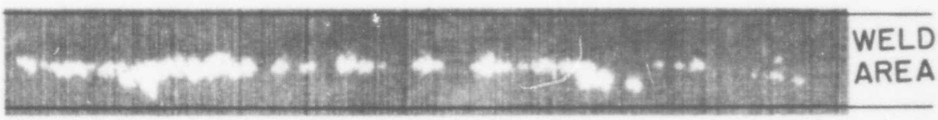
Figure 23. Profile of Weld Crown Configuration



"AS WELDED"



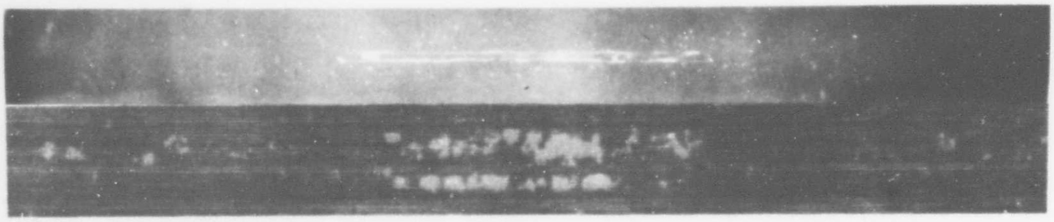
"BLENDED"



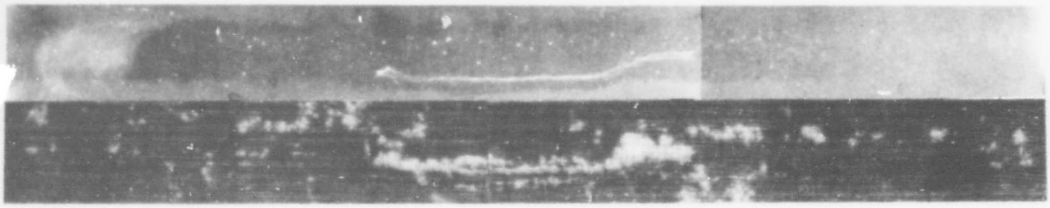
"FLUSH"

RESULTS OF INCREMENTAL CROWN BLENDING

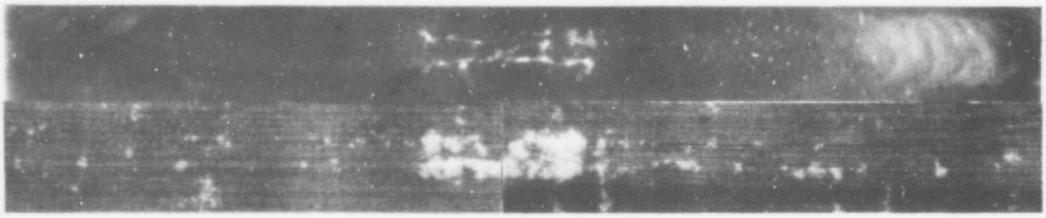
FIGURE NO. 24



PANEL I



PANEL J

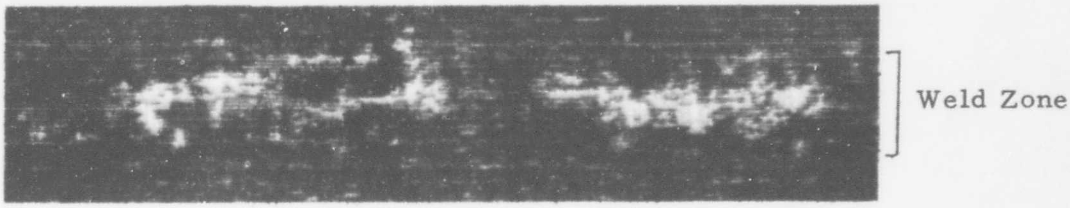


PANEL K

PANEL R

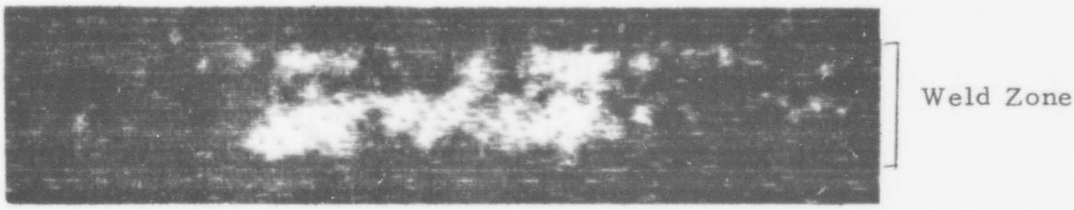
SINGLE RECEIVER / DUAL TRANSMITTER DELTA RECORDINGS, $\alpha = 23.5°$

FIGURE NO. 25



Major Defect in Weld Panel I

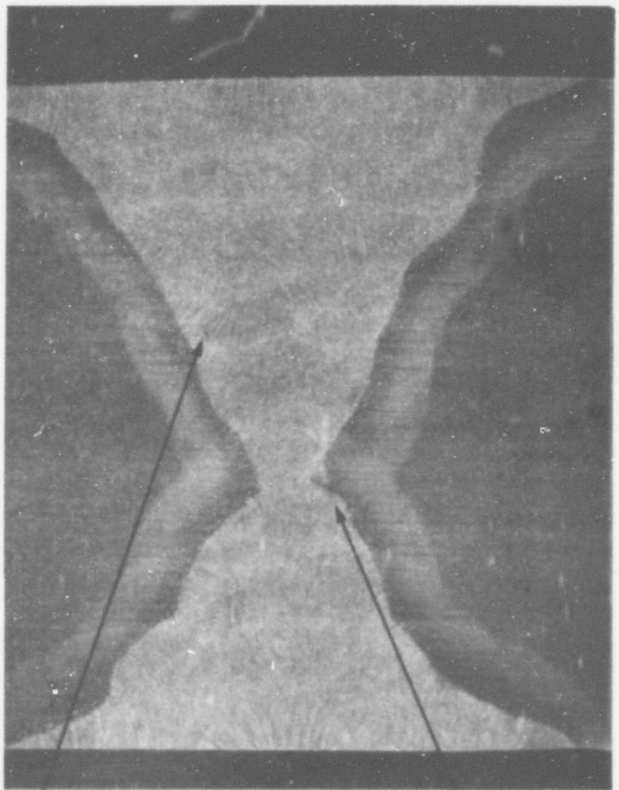
Major Defect in Weld Panel J



Major Defect in Weld Panel K

Figure No. 26. Delta Scan Recordings made with a Single Transmitter in the Shuttle Delta Fixture

Figure No. 27 Macrophoto of 1" Butt Weld

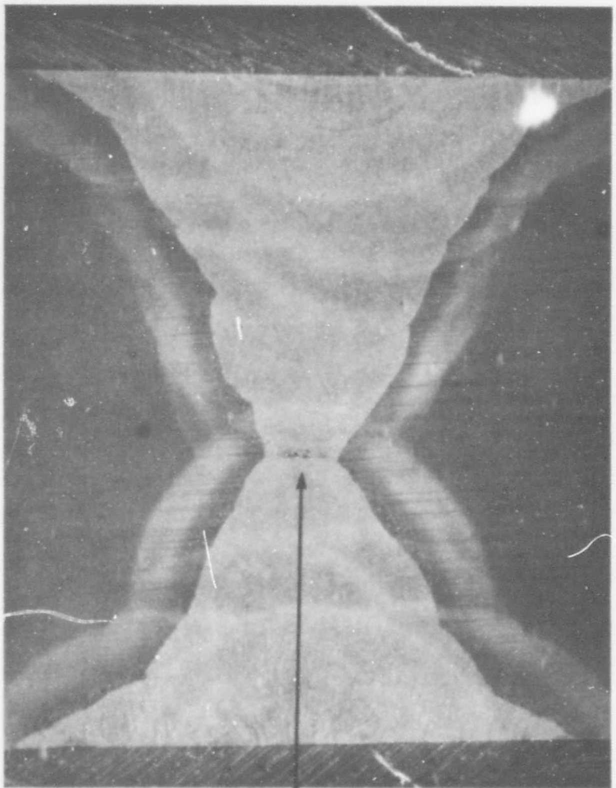


4X Nital Etch

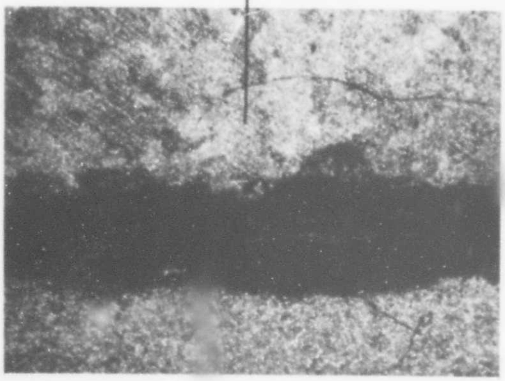
50X Nital Etch

50X Nital Etch

Figure No. 28A. Macro and Micro Photographs of Plate S

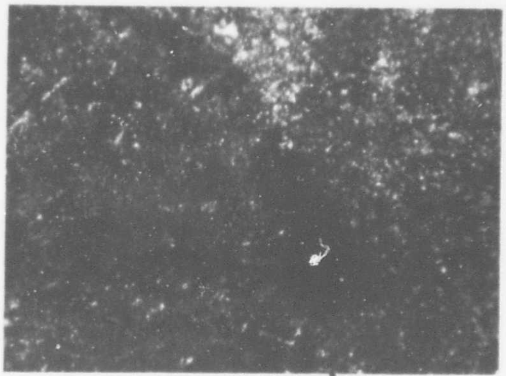


4X Nital Etch



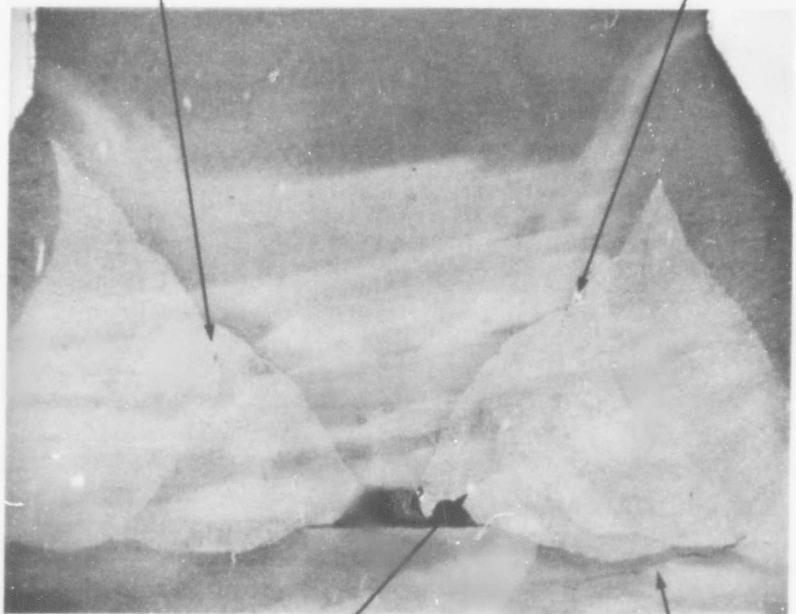
50X Nital Etch

Figure No. 28 B. Macro and Micro Photographs of Plate S

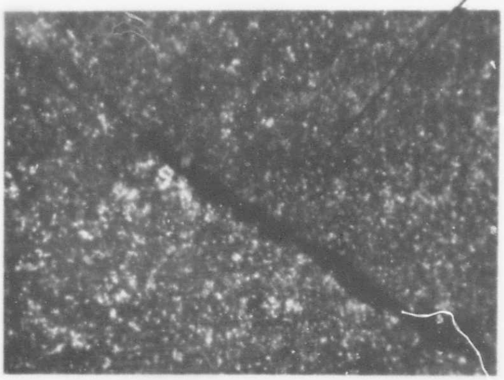


50X Nital Etch

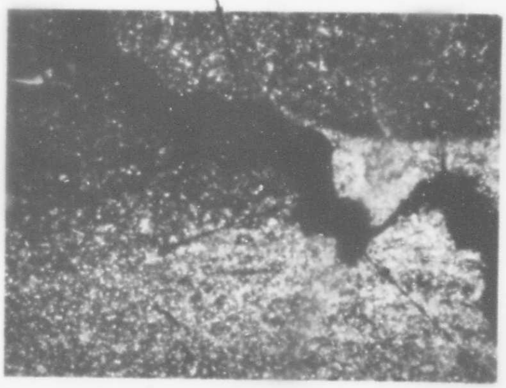
50X Nital Etch



3X Nital Etch



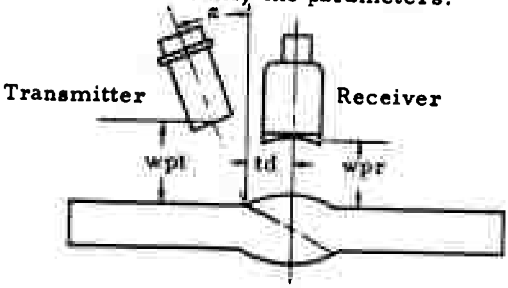
50X Nital Etch



50X Nital Etch

Figure No. 29. Tee Weld Destructive Test Results

This table lists the various parameters for Delta weld inspection for a given material of a thickness range of 0.500" to 1.250". See sketch to identify the parameters.



td - distance between the receiver axis and the point of incidence of the transmitted beam.

wpr - receiver water path.

wpt - transmitter water path.

Material: Mild steel
Longitudinal Velocity - 5.85 mm/µsec
Shear Velocity - 3.23 mm/µsec
Density - 7.8 gm/cm^3

For this material, angle *a* should be 23.5° for optimum results.

Weld Thickness	td	wpr	wpt	Transmitter Search Unit	Receiver Search Unit
0.500"	0.433"	1.625"	1.375"	0.375" diameter, ceramic element with a flat lens.	0.625" diameter lithium sulphate element with a sharp focus lens.
0.750"	0.650"	1.625"	1.375"	0.500" diameter, ceramic element with flat lens.	0.750" diameter lithium sulphate element with a sharp focus lens.
1.00"	0.866"	1.625"	1.375"	0.625" diameter, ceramic element with a flat lens.	0.750" diameter lithium sulphate element with a sharp focus lens.
1.250"	1.080"	1.625"	1.500"	0.750" diameter, ceramic element with a flat lens.	1.00" diameter lithium sulphate element with a medium focus lens.

Table I. Delta Parameters for Butt Weld Inspection

APPENDIX I

A complete list of the flaw detection and associated equipment used in the program is listed below:

Sperry Products, Reflectoscope, Type UM721
Sperry Products, Pulser/Receiver, Type UM, Style 50E533
Sperry Products, Pulser/Receiver, Type UM, Style 50E528
Sperry Products, Special Function Cabinet, Type UM710
Sperry Products, Transigate, Type UM, Style 50C753
Sperry Products, Transigraph Control, Type UM, Style 50E543
Sperry Products, Recording Amplifier, Type STF, Style 50A3159
Alden Electronic and Impulse Facsimile Recorder, Model 311DA
Automation Industries, Inc., Delta Manipulator, Style 57A4082
Automation Industries, Inc., Laboratory Type Immersion Automatic Scanning Tank, Model 57D4294
Automation Industries, Inc., Delta Shuttle Fixture, Model 57A4871
Automation Industries, Inc., Search Units,

Style No.	57A3623	57A3381
	57A3377	57A2685
	57A2689	57A2693
	57A2697	57A2804

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